Sonoluminescence: Making Light of an Unclear Past and Exploring the Path Forward

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To Alicia Casacchia, Aliyah Conley, and all the other members of the Ghost Class who are or have been involved with this project, thank you for helping make sonoluminescence a reality. I'm excited to see what the next few years have in store for this project.

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This is a Plan II SAWIAGOS project.

Parker Thomas George

Abstract

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Supervisor: Preston Wilson, Ph.D.
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Sonoluminescence is an acoustic phenomenon in which a bubble can be driven acoustically to collapse an emit a rapid burst of light. While this phenomenon was initially discovered in the 1930s, research in the field did not peak until 1989 when stable, single bubble sonoluminescence was observed and reported. The author will present an introduction and overview of this phenomenon, and then will provide a brief history of the key research findings in the field between the initial discovery and the present. In particular, the claim that "sonofusion" could be achieved will be addressed and unpacked. An argument will then be put forth that sonoluminescence was unfairly associated with this "sonofusion," and that this led to a decline in research in the field, particularly in the applied space. In response, the author will introduce a novel approach to using sonoluminescence as a medical screening tool, along with a suggestion for how such an apparatus could be constructed.

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Foreword

As crazy as it may seem, this entire project – *The Sonoluminescence Project*, as it has been affectionately named – began with a Wikipedia random article search during the Spring semester of my Freshman year. Owing to a personal decision to drop my engineering major and with the goal of transferring into business school, I found myself enrolled in Professor Marc Lewis' TC310: Modes of Reasoning. Though I did not necessarily need the course, the catalog description nonetheless sounded interesting, and the medical problem aspect of it appealed to my affection for left-brained activities.

Ironically, then, were it not for my decision to drop my mechanical engineering major, I never would have found myself at the center of such an exciting, innovative, and personally fulfilling engineering research project. In that respect, maybe the one semester I spent in the engineering program did add some lasting value.

Digressing, this thesis, this project, and the work that will continue after I graduate all started with the encouragement of Dr. Lewis' class to simply "research something interesting." The advice was not structured, and the bounds of what constituted research were particularly wide. One peer in my class group found a passion researching tardigrades (colloquially known as sea bears), and another spent a few months exploring a plant known to elicit the most painful sensation known to man, the Gympie gympie.

It was within this environment that I found sonoluminescence. At the time, the only reason I continued to dig deeper into the phenomenon was that it was simply a neat, "sciency" thing. I had no initial intentions of exploring its applications or constructing a device to produce the phenomenon. I simply wanted to learn more about it because I found the topic fascinating.

In that regard, this thesis is the culmination of exactly that. There are parts in this thesis that deserve their own manuscripts, and there are others that would benefit immensely from a deeper, more technical analysis that I am not of capable of writing. That said, a deep, technical dive into sonoluminescence is not the goal of this work. Instead, it is my hope that the reader comes away from this manuscript with a firm understanding of the history the research in the field, an appreciation of just how fascinating the phenomenon is, and an equally eager desire to see how sonoluminescence can change the world.

Chapter 1

Introduction

"Magic's just science we don't understand yet."

—Arthur C. Clarke

Put as simply as possible, sonoluminescence is the production of light from sound. More specifically, Sonoluminescnece is an acoustic phenomenon in which a bubble driven acoustically in a fluid medium will rapidly expand, contract and emit a rapid burst light. Figure 1.1 provides a fairly accurate graphical representation of this process. The bubble expands in size before rapidly collapsing. At the moment of collapse, a rapid burst of light is emitted. Getting more granular, there are two distinct types of sonoluminescence: Multi-bubble sonoluminescence (MBSL), discovered first, and single-bubble sonoluminescence (SBSL), which gained immense research popularity in the early 1990s.

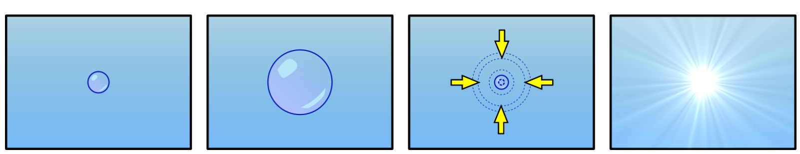


Figure 1.1: Sonoluminescence process[1]

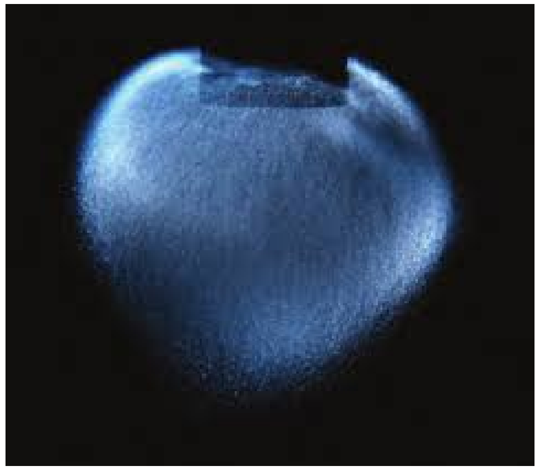


Figure 1.2: Multi-bubble sonoluminescence[3]

MBSL, as its name suggests, involves the emission of light from a number of small bubbles created by acoustic cavitation. Cavitation itself occurs when a liquid experiences rapid pressure changes. In areas that experience a low pressure, small bubbles can be formed. When these bubbles then encounter a high pressure area, the immense pressure gradient causes an expansion of the bubble followed by a rapid contraction of bubble radius, which compresses gas in the bubbles to extreme pressures and temperatures. This collapse generates intense, often noisy shock-waves and, when the conditions are correct, this collapse can produce a quick burst of light.[2] Figure 1.2 shows a long exposure taken of multi-bubble sonoluminscence. Each blip of light is the result of bubble, produced by cavitation, that then collapsed onto itself and sonoluminescesed.

SBSL, on the other hand, involves a single, typically man-made bubble that is manually or acoustically suspended in a fluid and is acoustically driven such that the bubble oscillates and luminesceses. Though the bubble in SBSL is typically manually generated and placed, rather than produced by cavitation, the same mechanisms apply here. The bubble is driven acoustically until it expands, rapidly collapses, and produces a quick, intense burst of light, before returning to its original, pre-expansion and collapse size. Figure 1.3 shows the luminescent moment of an SBSL experimental setup.

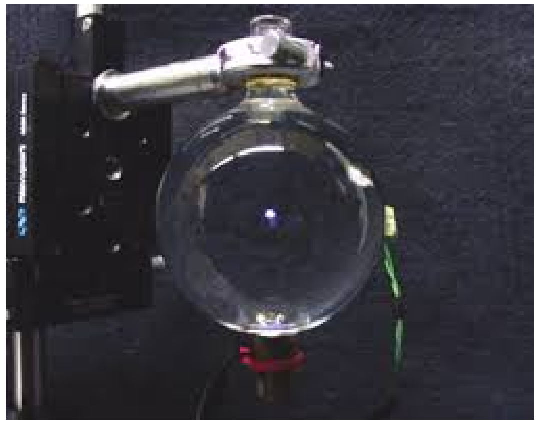


Figure 1.3: Single-bubble sonoluminescence[3]

(a) Chemiluminescence[4]

(b) Bioluminescent *Noctiluca scintillans*[5]

Figure 1.4: Other forms of luminescence in nature

sonoluminescence is not, though, the only “naturally” ocurring form of light production. As is likely more well known, other forms of light emission include bioluminescence and chemiluminescence, both of which can be seen in seen in Figure 1.4.

The light emission in these phenomena is the result of a chemical reaction, in particular oxidation. The operative difference between the mechanisms of these forms of luminescence and sonoluminescence is that sonoluminescence is driven by *mechanical* excitation, not chemical. Though the presence of certain chemicals, namely noble gasses, do significantly affect the sonoluminescence output, the presence of this gas is not the mechanism by which sonoluminescence is created. Though these other forms of luminescence are fascinating, they will not be the focus of this content presented in this thesis.

Interestingly, despite some of the extreme properties of sonoluminescnce (that will be described below), sonoluminescence is not a phenomenon that occurs exclusively in a laboratory. In fact, many who are familiar with the phenomenon have likely heard of it in connection to the the Pistol Shrimp and the Mantis Shrimp. These fascinating little creatures, *Alpheus digitalis* and *Odontodactylus scyllarus* produce sonoluminescence in their hunting process. Both creatures engage their prey by rapidly shutting one of their claws. This is done with enough acceleration and speed to produce a jet of pressure and cavitation. [6][7]. The collapse of the bubbles produced by this cavitation then generates extreme pressures and a sound of over 200 decibels which can stun or kill a small fish that is nearby.[8]. Sonoluminescence has been observed in the cavitation bubbles of both species, but current research suggests that this light emission is likely just a byproduct of the cavitation and does not play a direct role in the hunting process.[9]. Nevertheless, that these two little crustaceans can create such a phenomenon is particularly fascinating.[1]

Sonoluminescence Properties

Though sonoluminescence is a fascinating phenomenon in and of itself, a number of its properties are arguably even more fascinating and each have a portion of the research field dedicated to their study. Some of these include the temperature created at the moment of the sonoluminescence burst, the characterization of the bubble dynamics, the dependence upon the fluid temperature, pressure, the wavelength of the emitted light, and the speed at which the light is emitted. In addition to simply being neat, many of these will become relevant later in sections of this thesis.

[1]Engineers at Texas A&M University have succeeded in 3D-printing a scaled-up model of this claw that successfully produces cavitation when it closes. High speed video footage of this, which clearly shows the collapse of the bubble, can be found here `https://youtu.be/bCvGKW8H7HE`[10]

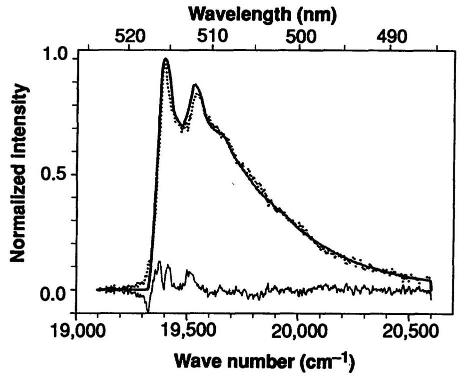


Figure 1.5: From Flint-Suslick, intensity-wavelength of sonoluminescence plotted with synthetic intensity-wavelength for temperatures ranging from 4600 K to 5300 K[11]

Temperature of the Collapse

One of these interesting properties is the extremely high temperatures achieved during sonoluminescent cavitation in MBSL. First posited in 1991 by University of Illinois Urbana-Champaign researchers Edward Flint and Kenneth Suslick, MBSL, the "effective temperature of the cavitation events responsible for sonoluminescence.... is 5075 $\pm$ 156 K."[11]. This measurement was obtained indirectly comparing the spectral output of sonoluminescence to a synthetically generated spectral output in this temperature range, as shown in Figure 1.5. This was a particularly exciting conclusion, because 5,000 K is extremely similar to the temperatures reached on the surface of the Sun.[12]. Though no fusion occurs at the surface of the sun, this temperature is immensely higher than typically encountered in organic science, and even rivals the temperature of the Earth's core.

Regarding SBSL, the temperature claims were even more extreme. One paper published by researchers in the UCLA Physics Department suggested that a high degree of similarity between the spectral intensity of room temperature SBSL and the spectral intensity of blackbody radiation at 25,000 K. At lower temperatures, (10 °C instead of 20–23 °C), the SBSL spectral intensity curve closely mirrors that of a 50,000 K blackbody.[13]. One paper even posited, theoretically, that "temperatures approaching 1000 eV [1.16×10^7 K] may be achievable through the manipulation of the driving pressure and minimization of molecular dissociation and ionization of the dissolved gasses.[14]

Though 11×10^7 K is orders of magnitude higher than temperatures posited and observed in MBSL, it is still a few orders of magnitude away from that which is traditionally accepted as required for fusion. Nevertheless, this extreme temperature from such a small, and relatively easily producible phenomenon, has piqued the interest of many chemists and physicists.

Temperature Dependency

Separate from the temperatures produced by sonoluminescence, research also shows that sonoluminescence light intensity is highly determined by the temperature of the fluid medium. According to one experiment by Barber and Putterman, decreasing the temperature of water in which sonoluminescence was conducted from 40 °C to 1 °C resulted in an increase in sonoluminescence intensity by more than a factor of 200, such that "at 1 °C the purple light emitted by the bubble is so bright that it can be seen by the unaided eye even in the presence of unaided light."[15]. Figure 1.6, reproduced form Barber and Putterman, shows the effect that temperature has on bubble radius, and consequently, on emission intensity.

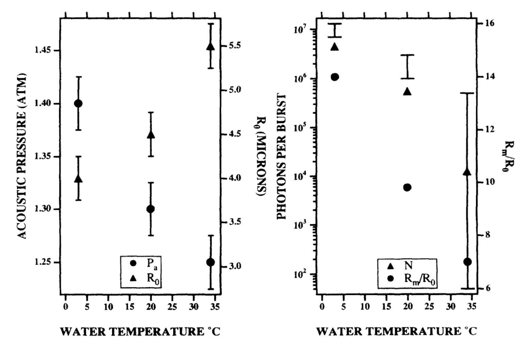


Figure 1.6: From Barber and Putterman, sonoluminescence intensity and bubble radius of an air bubble as a function of water temperatureplotted against radius (note the log scale of the "photons per burst" axis.)[15]

Bubble Dynamics

The expansion and collapse of a sonoluminescing bubble can described with a high degree of accuracy using the Rayleigh-Plesset equation, as proven experimentally by Hilgenfeldt et al. and [16] This equation, reproduced in 1.1, describes the radius (R) of a bubble during each oscillatory period as a function of time with respect to the second derivative of bubble radius with respect to time ($\ddot{R}$), the density of the liquid (ρ_t), the pressure in the gas bubble (p_g), the ambient pressure of the system (P_0), the applied acoustic pressure from the transducer ($P(t)$), the viscosity of the liquid (μ), the first derivative of bubble radius with respect to time ($dotR$), and the surface tension of the bubble-liquid interaction (γ).

$$R\ddot{R} + \frac{3}{2}R^2 = \frac{1}{\rho}\left(p_g - P_0 - P(t) - 4\mu\frac{\dot{R}}{R} - \frac{2\gamma}{R}\right) \tag{1.1}$$

Figures 1.7 and 1.8 show how this equation compares with experimental measurements of the radius of an acoustically driven bubble.[2] In both instances, three distinct phases can be seen during the period – an expansion, initial collapse, and then after-bounces before the bubble returns to its ambient size and begins the next oscillation period. As can be seen, the expansion and initial collapse phases track very nicely to the model produced from the Rayleigh-Plesset equation. Likewise, the after-bounces that occur following the initial collapse also mirror that of the Rayleigh-Plesset model, though with less accuracy than the expansion or collapse.[3]

Additionally, the intensity of the light emission from sonoluminescence can also be directly described using this equation, for Barber et al. have shown that the intensity of light

[2]Matula uses the Keller-Miksis formulation rather than the Rayleigh-Plesset equation. This formulation is derived in part from the Rayleigh-Plesset equation, and is a more accurate model of the bubble dynamics at the moment of collapse, for this derivation Rayleigh-Plesset cannot account for instances where the first order radius-time derivative exceeds the speed of sound in the fluid, as happens during the initial collapse in each oscillation. [17]

[3]Barber and Putteman also note a more significant discrepancy between the Rayleigh-Plesset model and the experimental measurements approximately .1 μs before and after the collapse reaches R_{min} and light is emitted. This is further explained in the footnote 2, above.[18]

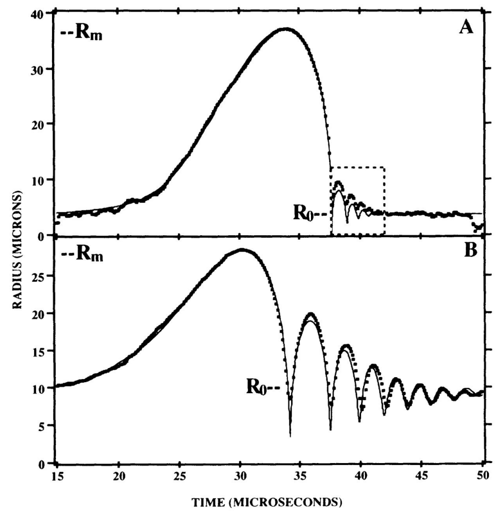


Figure 1.7: From Barber and Putterman, comparison of experimental bubble radius measurements (dots) with Rayleigh-Plesset equation (solid line), both for a sonoluminescing bubble (top) and a non-light-emitting bubble (bottom) [18]

output is highly dependent upon changes in radius. In specific, Barber et. al report that "Changes in bubble radius of only 20% are associated with factors of 200 in the intensity of emitted light."[15] Figure 1.9 demonstrates this relationship – as the magnitude of the difference between the maximum radius and the minimum radius increases, so to does the intensity of the sonoluminescence output. Figure 1.10, reproduced from the original SBSL paper published by Gaitan et al. further corroborates this finding, and demonstrates the second-order relationship that exists between radius and sonoluminescence intensity.

Bubble Size

As can be seen in Figures 1.9 and 1.10 Barber and Putterman report that the ambient bubble radius of an SBSL bubble is typically about 5 μm.[20] During the expansion phase of the oscillation period, the bubble radius then increases by roughly a factor of 10 up to 50 μm. During collapse, the bubble reaches a radius minimum of approximately .5 μm. It is this rapid radial collapse that generates the intense temperatures produced, Because the volume of the gas bubble is proportional to the cube of the radius, a radial collapse by a

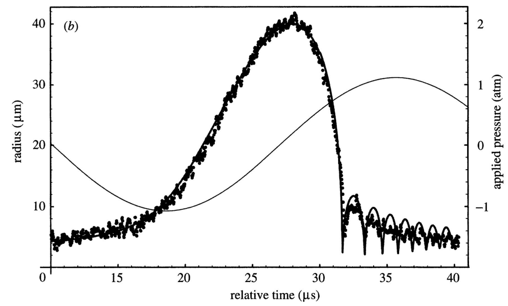


Figure 1.8: From Matula, comparison of experimental bubble radius measurements (dots) with an improved form of the Rayleigh-Plesset equation – the Keller-Miksis formulation (solid line). [19]

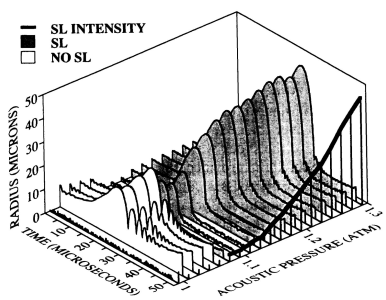


Figure 1.9: From Barber et. al, sonoluminescence intensity plotted against various magnitudes of $\frac{R_{max}}{R_{min}}$. [15]

factor of 1×10^2 gives rise to a volumetric collapse by a factor of 1×10^6.

Nevertheless, while most SBSL experiments involve bubbles that can be parameterized with the above measurements, such size measurements are not at all a minimum or maximum for the size of a bubble that can be driven to produces sonoluminescence. Gaitan et al.'s initial SBSL publications suggest bubbles with radii of approximately 20 μm.[21]

Given the more transient nature of bubbles in MBSL experiments, less research exists regarding measurements of the bubble sizes. Nevertheless, Lee et. al report a distribution of bubble sizes in a MBSL cavitation experiment in water from approximately of 2.9 μm to 3.75 μm, as shown in Figure 1.11.[22]

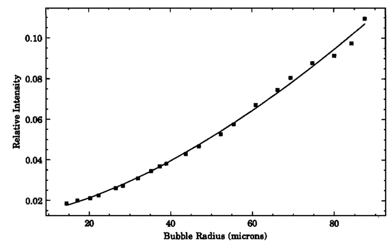


FIG. 8. Measured scattered light intensity versus equilibrium bubble radius for 42% glycerine. The solid line corresponds to a second degree polynomial fit.

Figure 1.10: From Gaitan et. al, sonoluminescence intensity plotted against radius, with a second-degree polynomial fitted to the data. [15]

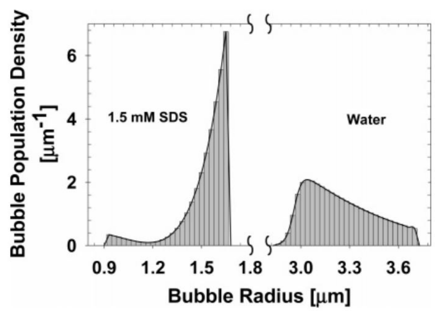


Figure 1.11: From Lee et al., population density of different bubble sizes in a sodium dodecyl sulfate solution (left) and in water (right).[22]

Duration of the Light Emission

Regarding light emission at the moment of collapse, research by Barber, Hiller, and Putterman indicates that the duration of each light emission is "conservatively less than 50 ps."[23]. This contradicted previous suggestions that the duration of light emission was much longer – on the order of 5 ns or possibly even as long as 5 μs).[23][24] This is extraordinarily fast – for scale, picoseconds is the unit of time used to describe the distance light travels (approximately 1 mm per ps in a vacuum). As another indication of this shear scale, one picosecond is to a second as a second is to approximately 32,000 years.

Chapter 2

Background

While the Pistol Shrimp may have "discovered" sonoluminescence approximately 400 million years ago, it was not until the 1930s that mankind first observed and documented it. Largely by accident, MBSL was first recorded in 1934 when two German scientists, Frenzel and Schultes, were using lithographic plates in an experiment involving caviatation. Though no light source was present in the experiment, the two continued to observe that the plates, upon removal from the experiment, had been darkened—exposed—by some unknown light source.[25]

French scientists Marinesco and Trilliat are also credited with an independent discovery of sonoluminescence in 1933, much in a similar way. In a report titled *Action of supersonic waves upon the photographic plate*, the French researchers also accidentally exposed their photosensitive plates despite the absence of an external light source. Here again, when the supersonic sound waves used in their experiment created created cavitation and sonoluminescence.[26]

Frenzel, Schultes, Marinesco, and Trilliat had been some of the first to observe sonoluminescence, but, owing to the lack of tools needed to clearly understand what was going on, they"'moved on to more interesting subjects.'"[1]

Following these discoveries, very little research was done involving sonolimunescence. A paper published in 1937 experimented with 36 different cavitated liquids and observed light emission in 14 of them.[28] This paper was particularly ahead of its time in that it the first to suggest that chemical differences in the fluid medium affected sonoluminescence output. It also ranked, using the naked eye, the intensities of light emission in those liquids where sonoluminescence was observed, and even went so far as to suggest that temperature of the liquid affected the intensity of the light emission.

Regarding the name, sonoluminescence, Princeton University researcher Harvey Newton is given credit from a paper published in 1939. "It is customary to designate a luminescence by the method of excitation" wrote Harvey.[29] Thus, the luminescence which appears when sound waves pass through liquids has been called acoustic or sonic luminescence, for short, sonoluminescence."[29].

Beyond that, while one can certainly find papers mentioning "sonoluminescence" published between 1940 and 1980, these papers tend to be more observational in nature.[30] With the exception of a paper published in 1960 by Peter Jarman which suggested the origin of sonoluminescenc was thermal rather than electrical, the majority of early sonoluminescence publications sought not to understand or explore the mechanism behind the phenomenon, but rather to explain what what sonoluminescence was report results experimental observations involving different fluids and gasses.[31]

This is hardly surprising. From its initial discovery in the 1930s up until the 1992, sonoluminescence was only known to exist in the MBSL form. Due to the transient nature

[1] Unable to find an English version of the original Frenzel and Schultes paper, this quote has instead been sourced from PhD thesis made available by the Neils Bohr Institute at the University of Copenhagen. A copy of this thesis can be found `https://www.nbi.ku.dk/english/research/phd_theses/phd_theses_2006/2006/jeppe_seidelin_dam.pdf`[27]

of cavitation, the inability to control when and where the caviation bubbles will appear, and the sheer number of luminescenct moments that occur when MBSL is happening, it can be extremely difficult both to measure and reliably replicate. Moreover, as seen through the 1937 paper by Leslie Chambers on the 36 different liquids, the technology needed to objectively and accurately measure light emission was simply not yet available. All of these made the phenomenon extremely hard both to measure and reliably replicate.

The eventual uptick in sonoluminescence publications was spearheaded by the breakthrough of Lawrence Crum and D. Felipe Gaitan, a professor and PhD student at The University of Mississippi, who succeeded in levitating and inducing sonoluminescence in a single bubble.[32][21] By acoustically creating a pressure node in the chamber, Crum and Gaitan were able to stably position the bubble in a relatively fixed location. As a result of this, the bubble could now be consistently photographed and recorded, and measurements of the sonoluminescence could be taken with much more precise instruments like hydrophones and photomultiplier tubes. This paved the way for nearly all ensuing sonoluminescence research projects, and resulted in over 1000 publications in the ensuing fifteen years.[33] In addition to this, as put by leading researcher Lawerence Crum, "papers were actually published claiming nuclear fusion, songs were written, and albums were sold—a multi-million dollar movie was even made about it."[33] sonoluminescence had fascinated the scientific community, and it responded with a storm of attention given to the subject.

However, while the jazz composition and the Keanu Reeves film are certainly worth at least mentioning, neither of these received anywhere near the attention that the suggestion that nuclear fusion was capable through sonoluminescence. This took the academic community by storm, and while there was certainly fallout, most was not of the nuclear kind.

Chapter 3

Fusion Controversey

As mentioned in the Chapter 1, for better or worse, sonoluminescence research did not reach its peak until the possibility of fusion was introduced. Spearheaded by just a few scientists, sonoluminescence immediately took the stage as the next path for “cold fusion,” even if the phenomenon was neither cold nor capable of fusion.

Tabletop fusion experiments were not necessairly a new thing in the 1990s. In 1989, an arguably infamous paper published by Chemists Martin Flesichmann and Stanley Pons, titled “Electrochemically induced nuclear fusion” reported table-top fusion using a palladium cathode and heavy water.[34] [1] In this experiment, Fleischmann and Pons observed energy outputs that were “10^2–10^3 times larger than the enthalpy of reaction of chemical processes” involved in the experiment. [35] They proposed that fusion was the probable explanation.

Unfortunately, though, this apparent scientific breakthrough would be short lived. Despite claiming that the experiment had been confirmed multiple times and that they were confident in their research, the academic community was on the whole unable to independently

[1] Heavy water, or deuterium oxide D_2O is water with the hydrogen atom replaced by the deuterium isotope of hydrogen, which has twice the atomic mass of regular hydrogen. Heavy water is frequently used in nuclear experiments and reactions.

verify and replicate their findings.[36] Efforts at the California Institute of Technology, Massachusetts Institute of Technology, The University of California, the University of Rochester, Brookhaven National Laboratory, and Yale University all failed at replicating the results of the experiment.

Only the Georgia Institute of Technology and Texas A&M University reported positive findings, but Georga Tech ultimately retracted their findings on the account of a false sensor reading.[37] To date, the Texas A&M experiment remains the only non-retracted positive confirmation of the Fleischmann-Pons experiment, but it itself is riddled with criticism and claims of scientific dishonesty. By late 1989, the Flesichmann-Pons discovery had all but been ruled dead.[2]

Nevertheless, table-top fusion was now fresh on the minds of scientists across all disciplines. Though cautious, researchers and the public alike recognized the immense possibility that clean, nuclear energy could provide, and chemists and physicists were undoubtedly drawn to the sci-fi appeal and massive potential upside that fusion research brought with it.

In addition to the possible upside that table-top fusion brought with it, it was also an extremely disruptive idea to the more large scale, industrial fusion experiments that were taking place. As recently as 2016, the leading design candidate for apparatus capable of producing nuclear fusion is the *Tokomak*, a torrodial shaped plasma collider that can be as large as 75 feet in diameter. In addition to the significant size constraints of such a device, the costs associated with constructing are also extraordinarily prohibitive. The International Thermonuclear Experimental Reactor (ITER) is the largest globally funded Tokomak fusion project, and costs associated with this build are expected to exceed € 20 billion, with over

[2]Fleischmann, Pons, and BYU professor Steven Jones continue to stand behind their initial findings and report, despite this widespread criticism and denouncement. Texas A&M professor John Bockris also stands behind his findings, even going so far as to publish a paper in 2000 that appeals to accountability and academic freedom as a defense of his findings and a response against the criticism he has received.[38]

€ 15 billion having already been spent by the end of 2015.[39] If a device were to come along that could produe similar results as is hoped for by the ITER at a fraction of a percent of the cost and size, this could potentially ruin the necessity for funding for these large-scale fusion projects. As a result, while the Fleischman-Pons experiment was certainly exciting to many, it was just as equally scary to others.

It was on the back of this wave of interest, excitement, and understandable concern that Rusi Taleyarkhan, then a physicist at the Oak Ridge National Laboratory in Tennessee delivered a paper in 2002 that shocked the sonoluminescence research field and the the entire scientific community as a whole. Published in the March 2002 edition of Science, Taleyarkhan bold claimed that he had achieved evidence of fusion using sonoluminescence.[40]

As an interesting aside, the possibility of sonoluminescence-induced fusion was not exactly a novel idea. Six years earlier in 1996, researchers at the Lawrence Livermore National Laboratory demonstrated that sonoluminescence in the presence of D_2, D_2O, and a mechanically induced pressure spike would make deuterium-deuterium fusion *theoretically* possible. [41]

Despite this seemingly fascinating theoretical breakthrough, the paper did not seem to receive much attention. A rudimentary search through Google Scholar's "cited by" function shows that, in the years following its publication in 1996 but before the 2002 Taleyarkhan publication, this article was not cited nearly as much as it has been after Taleyarkhan's publications. Moreover, of the times it was cited, more credence was given to the paper's sonoluminescence temperature measurements, and less to the potentially ground-breaking possibility of sonoluminescence induced nuclear fusion.

Digressing, Taleyarkhan's publications would and did change this. Boldly titled "Evidence for nuclear emissions during acoustic cativation", Taleyarkhan made no attempt to hedge his findings, and was even more assertive in the paper's abstract, reproduced below below:

In cavitation experiments with deuterated acetone, tritium decay activity above background levels was detected. In addition, evidence for neutron emission near 2.5 million electron volts was also observed, as would be expected for deuterium-deuterium fusion. Control experiments with normal acetone did not result in tritium activity or neutron emissions. Hydrodynamic shock code simulations supported the observed data and indicated highly compressed, hot (10^6 to 10^7 kelvin) bubble implosion conditions, as required for nuclear fusion reactions.[40]

Just as with the Fleischmann-Pons experiment, the deterium isotope was used to replace the hydrogen atom in the fluid used in the experiment. Rather than water, though, Taleyarkhan used degassed deutered acetone C_3D_6O at temperatures of 0 °C. This organic compound, at this temperature, was selected with the intent to maximize energy concentration during the bubble implosion moment. With these conditions, the radius of a sonoluminescing bubble could increase by a factor of 10^5.[40]. Traditional sonoluminescene experiments observed radius expansion only on the order of 10^1. As a consequence of this, the energy concentration during a sonoluminescence implosion would be higher be a factor of 10^{12}.[40]. This massive increase in energy concentration should, in theory, provide a catalyst for fusion reactions to occur.

Refraining still from commenting on the validity of Taleyarkhan's results, his method was particularly intriguing. Though an explanation is beyond the scope of this thesis, a deuterium-deuterium D−D fusion reaction can take one of the following forms, each with a roughly equal likelihood of happening:[42]

$$ {}_1^2\mathrm{D} + {}_1^2\mathrm{D} \rightarrow {}_1^3\mathrm{T}\,(1.01\ \mathrm{MeV}) + p^+(3.02\ \mathrm{MeV}) \tag{3.1}$$

and

$$ {}_1^2\mathrm{D} + {}_1^2\mathrm{D} \rightarrow {}_2^3\mathrm{He}\,(0.82\ \mathrm{MeV}) + n^0(2.45\ \mathrm{MeV}) \tag{3.2}$$

Reaction 3.1 yields tritium, and reaction 3.2 yields helium. Given that each result is equally likely, the measured presence of one should, with a high enough sample size, offer statistically reliable evidence that both reactions had occurred.

To test for for evidence of the first reaction, Taleyarkhan elected to test for tritium production, and his results are shown below below.

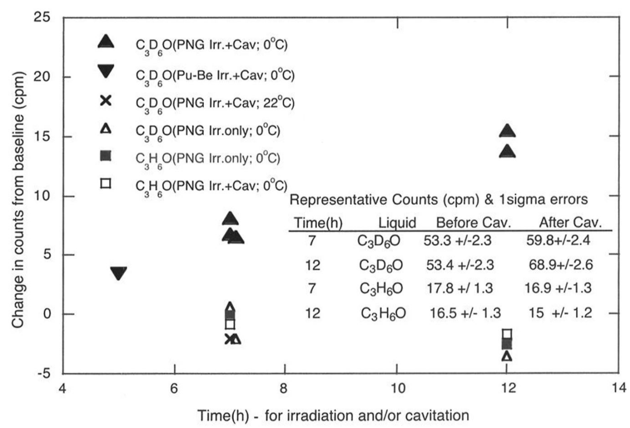


Fig. 3. T activity changes for C_3D_6O and C_3H_6O with irradiation (Irr.) and with irradiation plus cavitation (at 0°C). For C_3D_6O and C_3H_6O, 1 SD = ~3.5 cpm and ~2 cpm. PNG irradiation was at ~10^6 neutrons/s for specified time durations. All testing was conducted under the same configuration, placing the test cell under a vacuum of ~10 kPa.

Figure 3.1: From Taleyarkhan, the change in tritium counts for C_3H_6O and C_3D_6O with with and without cavitation, at 0 °C and 22 °C.[40]

Though it may not seem like much, it is this chart that would seem to offer rather definitive evidence that fusion had occurred. C_3H_6O at 0 °C, experienced no significant increase in tritium count at both 7 and 12 hours, regardless of whether or not cavitation was present in the experiment. Likewise, C_3D_6O at 0 °C without the presence of cavitation, represented by the empty triangle, also experienced no significant increase in tritium counts at 7 or 12 hours. Likewise, C_3H_6O at 22 °C, represented by the empty "X", also experienced no significant increase in tritium counts at 7 or 12 hours.

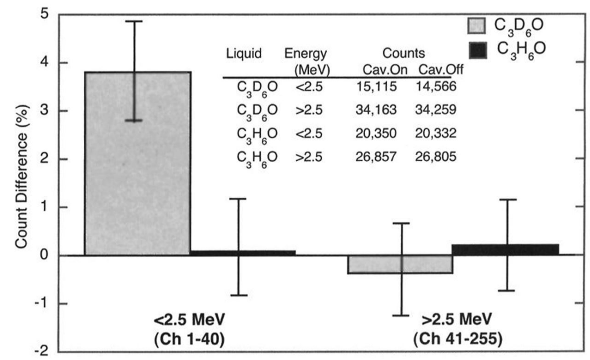


Fig. 4. Changes in counts for C_3D_6O and C_3H_6O with and without cavitation (Cav.). Error bars are 1 SD; data were taken over 100 s; and the percentage change in the <2.5-MeV range was found to be similar in magnitude for 300-s data acquisition times.

Figure 3.2: From Taleyarkhan, the change in neutron counts for C_3H_6O and C_3D_6O from before and after cavitation.[40]

However, C_3D_6O at 0 °C, in the presence of cavitation, experienced a significant increase in tritium counts both at 7 and 12 hours, both when exposed to neutrons by a plutonium-beryllium neutron source and by a pulsed neutron generator.

With the production of tritium reportedly detected, Taleyakhan then turned to the second reaction by measuring for neutron production in the reaction. Figure 3.2, reproduced from Taleyarkhan's paper, shows the results of this experiment for C_3H_6O and C_3D_6O at levels above and below the 2.5 MeV range.[3]

With measurements taken at durations between 100 seconds and 300 seconds, and given that the pulsed neutron generator was introducing neutrons at a rate of 500 neutrons per second, the population of neutrons in the experiment would have ranged from roughly 50,000 to 150,000.[40] Provided this, Taleyarkhan suggested that a Poisson distribution could be appropriately assumed. Given this, a 4 % increase in neutron counts, as seen in the left-most bar of Figure 3.2 would represent a statistically significant increase in neutron production

[3]From the paper, "2.5 MeV" encompasses 2.5 MeV neutrons consistent with those expected from the result of equation 3.2.

over the background production from the pulsed neutron generator. Evidence of the second possible outcome of a D-D fusion reaction.

Taleyarkhan's paper shocked the world of sonoluminescence and the scientific community as a whole. Almost immediately, though, Taleyarkhan's discovery was met with skepticism. Before the 2002 paper was even published, Oak Ridge's deputy director, Lee Reidinger, ordered an independent internal investigation.[43]

Dan Shapira and Michael Saltmarsh, two other Oak Ridge physicists, would undertake this. Using what multiple sources view was "a more-sensitive neutron detector," the duo arrived at the conclusion that "there [was] no evidence for any neutron excess due to fusion."[43] Justifying this, Saltmarsh argued that for the tritium production claimed in Taleyarkhan's findings (see Figure 3.1, the observed increase in neutrons should have been on the order of one order of magnitude, not the 1–4 % that was reported and in 3.2.[44]

This failure to obtain consistent results, and the attribution of increased neutron counts to "left over[s] from the 14 MeV neutrons fired into the cylinder," led Oak Ridge to independently contact Don Kennedy, editor-in-chief of *Science* attempting to withdraw their permission to publish Taleyarkhan's paper. [43] Rather than heed to the concern, Kennedy instead took offense, and remarked in an interview with *Science Magazine* writer Charles Seife that he was "'annoyed at the assumptions that nonauthors had the authority to tell [them] we couldn't publish the paper."' [44]

This dissent against the paper's publication was further reiterated by physicists William Happer, from Princeton, and Richard Garwin, of IBM's Thomas Watson laboratory. Calling on the recently submitted paper by Shapira and Saltmarsh, "Nuclear Fusion in Collapsing Bubbles - Is it There?", Happer and Garwin each encouraged Kennedy to at least co-publish Shapira and Saltmarsh's results alongside Takeyarkhan's as a hedge against the possibility of Taleyarkhan's findings being incorrect.[44][43] "For God's sake, don't put it on the cover," Happer reportedly once remarked to Kennedy. [43]

Nevertheless, *Science* went on to publish the article. Regarding what this meant for the credibility of the journal, Kennedy took a particularly noteworthy stance. "publication in *Science* certifies only that Taleyarkhan's paper has cleared the magazine's own peer-review and editing process. After that, it's up to the scientists." Going even further, Kennedy was quoted as saying "We're not wise enough to certify that every claim will stand up to the active effort of replication."[43]. Pressed further, Kennedy also published an editorial that directly addressed the controversy that surrounded *Science's* decision to publish the article. The excerpt below present's the crux of the issue:

> I have been asked, "Why are you going forward with a paper attached to so much controversy?" Well, that's what we do; our mission is to put interesting, potentially important science into public view after ensuring its quality as best as we possibly can. After that, efforts at repetition and reinterpretation can take place out in the open. That's where it belongs, not in an alternative universe in which anonymity prevails, rumor leaks out, and facts stay inside. It goes without saying that we cannot publish papers with a guarantee that every result is right. We're not that smart. That is why we are prepared for occasional disappointment when our internal judgments and our processes of external review turn out to be wrong, and a provocative result is not fully confirmed. What we ARE very sure of is that publication is the right option, even–and perhaps especially–when there is some controversy. [45]

As a further attempt to disprove the findings of Taleyarkhan, professors from the University of Illinois at Urbana-Champaign Yuri Didenko and Kenneth Suslick took to *Nature* to voice their concerns about the theoretical underpinnings of Taleyarkhan's experimental apparatus and results. In their paper, "The energy efficiency of formations of photons, radicals and ions during single-bubble cavitation," Didenko and Suslick present an an experimental setup and results using single bubble sonoluminescence, but then conclude the paper in a way that seems to tacitly discredit Taleyarkhan's.[46] Though there is no direct mention of "multi-bubble sonoluminescence" or "MBSL" anywhere in the document, the penultimate paragraph calls Taleyarkhan's results to the stand and declares them "highly controversial," referencing an article posted in /textitPhysics Today that itself contained no experiment and instead simply presented the skepticism and controversy.[47]

More directly, Didenko and Suslick end the paper with the comment that "the temperatures reached during cavitation [using acetone] will be substantially limited by the endothermic chemical reactions of the poly-atomic molecules inside the collapsing bubble. As a result they "therefore expect that the extraordinary conditions necessary to initiate nuclear fusion will be exceedingly difficult to obtain in any liquid with a significant vapor pressure."[46]. Despite experimenting with a wholly different type of sonoluminescence, and failing to address any specific shortcomings of Taleyarkhan's experimental setup or technique, Didenko and Suslick managed to deliver a paper that furthered the support against Taleyarkhan.

With the spread of the Shapira-Saltmarsh findings and now the Didenko-Suslick paper, the court of public opinion began to deliver its verdict. One e-letter to the editor attached to the online publication of the editorial written by Princeton professor Robert Austin went so far as to accuse *Science* of "irresponsible journalism" and of pushing an "extremely dubious result." [45] Even worse, various news sources and scientific magazines also weighed in on the issue, and the overwhelming opinion was that Taleyarkhan was incorrect and possibility even fraudulent.

Nevertheless, Taleyarkhan's fusion research did not stop there. On the back of the popularity of the 2002 publication, Taleyarkhan was invited to the Purdue University by Lefteri Tsoukalas, the head of the School of Nuclear Engineering. Taleyarkhan was ultimately hired in the Fall of 2003 with the goal of continuing the fusion research.

This culminated in a paper, drafted by Tsoukalas in 2003, claiming that Taleyarkhan's fusion findings *had* been replicated. This paper, which was not co-authored by Taleyarkhan, claimed in its abstract that "The results with the Beckman [neutron] detector point to statistically observable tritium increases in post-cavitation deuterated acetone samples, suggesting the possibility of D-D fusion taking place."[48][4] Interestingly, though, this paper never made it to the NURETH-11 conference for which it was intended.[5]. Upon initial inspection by Purdue professor Martin Bertodano, it was suggested that the data confirming Taleyarkhan's results should be removed. A revised draft with this data excluded was supposedly sent, but the paper was ultimately rescinded before the conference on account of concern from some of the listed authors.[49] Unfortunately for Taleyarkhan, this paper, which would have offered the first successful replication of his results, never saw the light of day.

In an attempt to address concerns about the presence of an external neutron source, Taleyarkhan published a second fusion paper in 2004, this time in Physical Review. As with his 2002 paper, Taleyarkhan concluded here that "large and statistically significant emissions of 2.5 MeV and below neutrons were noted during cavitation experiments in chilled deuterated acetone." More importantly, though, Taleyarkhan noted that "this neutron emission was well separated in time from the neutrons generated by the PNG,...and was time correlated with SL light emissions during bubble implosion events."[50]. Finally, Taleyarkhan also added test for fusion: gamma ray emissions. As with the presence of excess neutrons and tritium, "statistically significant gamma ray emissions were also measured in cavitation experiments with chilled C_3D_6O."[50]

A few months after the publication of this second paper, UCLA physicist Seth Putterman began his attempt to create sonofusion. Sponsored by the British Broadcasting Company

[4]The manuscript cited is an early copy of the manuscript. The abstract submitted to the NURETH-11 conference includes authorship by Tsouklas, in addition to Bougaev, Walters, and six other authors.

[5]Nuclear Reactor Thermal Hydraulics

(BBC) which hoped to film content for its long-running science documentary show, *Horizon*. [6][7] Unfortunately, though, despite the shows claim that "the recipe for fusion laid out in Rusi Taleyarkhan's published papers had been followed as closely as possible," the Putterman group was unable to achieve any signs of fusion.[51]

Despite the airing of the BBC episode in February 2005, the Putterman group did not publish a paper on the experiment until two years later in February 2007. This has sparked criticism from proponents of sonofusion for two reasons.[52] First, despite claiming in the BBC episode that all attempts were made to follow the "recipe" Taleyarkhan laid in his fusion papers, Putterman has also gone on the record, two years prior to receiving the BBC funding, stating that "We will not morph our project in order to reproduce an experiment that provides no new evidence for sonofusion."[53] In an experiment that is supposed to be replicative in nature, this rigidity seems odd and out of place. Putterman likely intended this to mean that he and his group would not manipulate their experimental setup to fabricate results, but this nonetheless carries with it a suggestion that he was not open to simply replicating Taleyarkhan's setup as perfectly as possible.

Second, the Putterman technique demanded that excess neutron production must be coincident to the sonoluminescence emission from collapsing bubbles. More specifically, "a scintillation event [was] deemed to ocurr from 100 ns before until 500 ns after the peak in the PMT response."[54] Interpreting this slightly, a neutron possibly produced by fusion would only be measured in this setup if it occurred within 100–500 ns after a sonoluminescence burst was detected the system. The goal, according to the paper, was to ensure that any observed excess neutrons could be causatively connected to sonoluminescence emissions, rather than some other, unknown source./cite With this criteria, the Putterman group was wholly unable to observe and report any instances of coincident neutron production. Per the

[6] A complete transcript of the BBC Horizon episode can be found here`http://newenergytimes.com/v2/bubblegate/2005/BBC-HORIZON-An-ExperimentToSaveTheWorld.pdf`

[7] A copy of the complete episode can be found here `https://www.youtube.com/watch?v=OCN1gAu1Hys` (Link checked 4/18/2019).

paper, "In none of the cases where 2 PMT's recorded an SL event was that event coincident with a neutron within a 1 μs window."[54] Lowering the tolerance level by an order of magnitude, "There [was] only one event where a neutron was coincident with the response of a single SL PMT within the 10 μs window that would characterize a bubble fusion event."[54]. From this, the scientists concluded a null result. In defense of sonofusion, though, the authors write that "the null result reported here does not change our opinion that the search for cavitation driven thermonuclear fusion is a worthwhile high risk endeavor."[54].

In spite of this, Taleyarkhan pressed forward, and released yet another paper, published in Physical Review Letters on January 27, 2006. This paper, titled "Nuclear Emissions During Self-Nucleated Acoustic Cavitation," once again reasserted and defended the initial observation of fusion byproducts–tritium and neutrons. Importantly, though, the experimental apparatus used in the experiments published in this paper did *not* contain an external neutron source. This was key, for it "resolve[d] any lingering confusion associated with the possible influence of the previously used external neutrons (14.1 MeV on the emitted neutrons (2.45 MeV)."[55].

Then, on February 28, 2006, Tsoukalas and a group of researchers at the School of Nuclear Engineering at Purdue submitted their own findings (or lack thereof) related to sonofusion to the Journal of Nuclear Technology. Here, they noted that"the average number of disintegratons per minute observation is within 1 σ of zero."[48]. They also presented their tritium findings in a graph similar to that of Taleyarkhan's. The graph, reproduced in Figure 3.3, clearly demonstrates an absence of increased tritium measurements from deuterated acetone (D-acetone), which was a hallmark of Taleyarkhan's findings, as seen in Figure 3.2.[8]

[8]Tsoukalas et al. submitted this paper on February 28, 2006. However, it was not published until August 2006. Thus, any suggestions that this paper was published in attempt to add post-hoc evidence to the Taleyarkhan investigation would be incorrect. The paper was submitted prior to the announcement that an investigation was underway. Information about this investigation can be found in Appendix A.

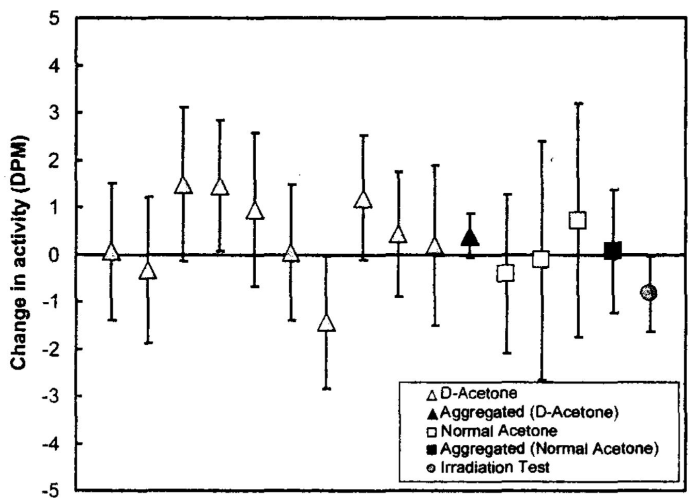


Fig. 6. Tritium measurements.

Figure 3.3: From Tsoukalas et al, the change in tritium counts for cavitated and uncavitated acetone and deuterated acetone. [48]

Later that year, sometime over the summer of 2006, Professor Edward Forringer and two students of LeTourneau University in Longview, Texas authored a paper which claimed to have independently tested and replicated Taleyarkhan's neutron measurements, observing "neutron production during self-nucleated acoustic cavitation of a mixture of deuterated acetone and benzine."[56] Interestingly, though, the introduction to this article indicates that the research was conducted on a visit to Purdue's meta-stable fluids research lab, and not at LeTourneau University. While this paper was published in the 95th volume of the Transactions of the American Nuclear Society, the fact that the work was conducted at Purdue rather than LeTourneau seems to have significantly limited the attention that one would expect such a replication to attempt to receive.

University of Tennessee professor Bill Bugg reported similar findings in a letter sent to Taleyarkan. Reporting on a trip Bugg took to Pudue and to Taleyarkhan's lab, Bugg wrote that "he [found] a statistically significant excess of neutrons over the background in the 2 deuterated sample detectors...and none in the undeuterated sample."[57] As with the

LeTourneau group, this observation was also made from Takeyarkhan's lab, not an independent one. Bugg even goes so far as to thank Taleyarkhan for his "willingness to let [Bugg] participate (and interfere) in [Taleyarkhan's] experiments."[57] Thus, Bugg's observations may be more appropriately called an observation of Taleyarkhan's experiment rather than his own, independent findings.

As hopefully demonstrated above, by the end of 2006 there still appeared to be no unanimous consensus by the academic community on whether or not Taleyarkhan had achieved nuclear fusion from sonoluminescence. For Taleyarkhan, this 2006 paper would be the last fusion paper he would publish. The months and years following would go on to consist of investigation after investigation by Purdue University and by the House of Representatives Committee on Science and Technology. For a summary of these proceedings and their findings, see Appendix A.

Chapter 4

Credibility of Sonofusion

Taleyarkhan's unwavering support of his 2002, 2004, and 2006 papers in the face of their near complete rejection by the academic community warrants an interesting discussion about the standard by which science judges whether or not a result is "correct." By the end of 2006, only Suslick, Shapira-Saltmarsh, Putterman, Xu-Butt, Forringer, and Bugg had put forth attempts to replicate the Taleyarkhan experiment and achieve consistent fusion results, as Taleyarkhan had. However, as shown in Chapter 3, the Suslick, Shapira-Saltmarsh, and Putterman experiments each had certain design differences compared to Taleyarkhan's setup in such a way that one could argue prevent each experiment from completely refuting the results reported by Taleyarkhan's apparatus. On the other hand, the researchers that had published or announced confirmatory results–Xu-Butt, Forringer, and Bugg – all had some degree of interaction with Taleyarkhan's lab or expertise, which equally raises questions about the validity and independence of these confirmations.[1]

With only 6 attempts having been made to replicate Taleyarkhan's fusion results, and with each of these attempts having some detail that may negate them from representing a perfect replication attempt, is this enough to rule that Taleyarkhan's reports of fusion were

[1] Appendix A provides further detail about the Xu-Butt publications and Taleyarkhan's connection to them

incorrect? If not, then how much more evidence should be required before this claim can be made? The goal here is not to comment on the quality or validity of any of these specific attempts, but rather to press the issue of how, why, and when the academic community accepts something as fact, and to challenge whether or not this standard was fairly applied to Taleyarkhan and his fusion claims.

Two, arguably competing factors are in play here. The first is the question of what makes a claim factual. The second, more particular to the potentially world-changing claim of fusion production, is the idea that extraordinary claims require extraordinary evidence. The former seeks to address what kind of evidence, and how much of it, is needed to empirically prove something as correct. The later seeks to condition this based upon the significance of the claim made.

Regarding the first factor, at the surface level, facts should be binary. $1 = 1$ is either "True" or "False" – a fact or not a fact. In traditional math, there will never be a scenario where the outcome of this unknown or uncertain. This can be proven mathematically, and just as well can be proven observationally. "There is one ball on this table and one ball on that table; are the number of balls on each table equal?" When the answer to this question is yes, the statement that $1 = 1$ can be proven true.

Likewise, Taleyarkhan's claim of fusion should give rise to a similarly binary result. Either fusion did occur, or it did not. The problem, though, is that Taleyarkhan's fusion observations are not observable in the way that the claim of $1 = 1$ can be. Suslick, Shapira-Saltmarsh, and Putterman all constructed their own apparatuses, and in doing so introduced a degree of variability in the system. Similarly, Xu-Butt, Forringer, and Bugg, though Taleyarkhan's equipment may have been used, nonetheless conducted their own experiments, which also added that degree of variability and subjectivity. As a consequence of this, inference and speculation play a role in how each experiment is used to comment on the factual nature of Taleyarkhan's claims. Specifically, inference and speculation must be used to bridge the gap between the findings of each replication attempt and the claims of Taleyarkan's. Were each experiment to have been a perfect replication with Taleyarkhan's help (but not direction), perhaps the results of such experiment could be treated in a similar way to the "balls on the table" scenario mentioned above. Instead, each group of scientists is forced to draw a conclusion that "the findings of my experiments *mean* that the findings of Taleyarkhan's experiments were incorrect."

This is now no longer a binary situation. A good replication attempt should lead to a higher degree of confidence in this inference, and a worse replication attempt should lead to a lower one. Given though that what separates a "good" replication from a "bad" one can be difficult to quantify and qualify, this could possibly mitigated statistically with the law of large numbers. Given a large enough sample size, the variability of replication quality should average out, and a large enough sample size should asymptotically approach the true result of the original claim. If 100 or 1000 attempts are made to replicate, provided these are all based on some sort of evidence or experimental grounding, then perhaps this would be "enough" evidence that the inferences made from these experiments, on average, are indicative of the true result of the original experiment's claim. This would solve the issue created by inference and supposition because it returns the conclusion back to a decently binary one.

Unfortunately, the answer to the question of how large this sample needs to be is not as simple as the classical suggestion that $n = 30$ is "enough." Instead, this heavily depends the type of claim or result being made. Just as the clinical trial process for the release of a new medical drug is long and multi-faceted, claims that have much at stake necessarily need a higher degree of certainty than others, and this higher degree of certainty requires either a large number of confident, successful tests or the assurance that the tests which do report successful outcomes are robust and well enough designed to be satisfactory replications. This brings into play the second of the two factors at stake here.

The late astronomer Carl Sagan made famous the aphorism that "extraordinary claims require extraordinary evidence." Such a quote can even be traced back to David Hume.[58]. Regardless of the original source, the implication is simple. Claims that are particularly extraordinary in nature demand extraordinary evidence. As explained in the opening of Chapter 3, Taleyarkhan's claims of fusion from sonoluminescence certainly meet the criteria for "extraordinary." If true, they could revolutionize energy production while simultaneously undermining other efforts at clean energy.

So Taleyarkhan's fusion claims certainly require extraordinary evidence, but what qualifies as extraordinary evidence? The law of large numbers, referenced above, suggests that extraordinary evidence could could come in the form of an extraordinary quantity of evidence. But how much, then? Rather neatly, Bayes' theorem may provide an answer, or at least a framework in which to consider postulate an answer. As depicted in 4.1, Bayes' theorem is a method of calculating conditional probabilities – the probabilities of one thing conditioned by the probability another. Using this, we can begin to calculate the likelihood that an extraordinary claim is true, given how extraordinary the evidence is in favor of such a claim.

$$P(A \mid B) = \frac{P(B \mid A)\, P(A)}{P(B)} \tag{4.1}$$

As an example, consider the claim that someone could guess which number a six-sided die would produce nearly every time it were thrown. Provided the die is weighted evenly, the near perfect ability to guess this would almost certainly be extraordinary. But just how much evidence would we need in order to feel comfortable accepting this seemingly psychic claim? Bayes' theorem can roughly provide an answer. If we interpret "nearly every time" to mean 95% of the time, assume that the true probability of our friend being psychic is about one-in-a-billion, and know that the probability of a die landing on any of its six sides is one in six, or ˜ .167, then we can fill out Bayes' theorem as is done in 4.2, and conclude that the likelihood that our friend is psychic, given only one throw of the die, is extremely low

– just about 5 in-a-billion. Re-contextualizing, this calculation indicates that the evidence, $P(B)$ is just not extraordinary enough to confidently substantiate a claim.

$$5.69 \times 10^{-9} = \frac{.95 * 1 \times 10^{-9}}{\frac{1}{6}} \tag{4.2}$$

At 10 correct guesses, though, the likelihood of our friend guessing soars to .054, or a little more than one-in-twenty. At 11 guesses, this jumps again to .33, now almost one-in-three. Perhaps now we may be comfortable believing our friend is not guessing after all. More specifically, maybe 11 correct guesses is extraordinary evidence.[2] Even though the likelihood our friend is a psychic is just one-in-a-billion, the presence of this evidence now makes this likelihood much higher. This is Bayes' theorem in action.

This same logic can be applied to claims about fusion. Assigning descriptions to each variable, $P(A \mid B)$ would represent the likelihood that Taleyarkhan's claim of observing fusion is correct given the totality of the evidence presented. $P(B \mid A)$ would represent the likelihood of the evidence presented given that Taleyarkhan's claim were true. $P(A)$ would then represent the likelihood that Taleyarkhan's claim was truthful, and $P(B)$ would lastly represent the likelihood of the evidence in favor of the claim.

Assigning descriptions to each variable, $P(A \mid B)$ would represent the likelihood that Taleyarkhan observed fusion given the evidence presented. $P(B \mid A)$ would represent the likelihood that evidence of fusion would exist if Taleyarkhan did observe fusion. $P(A)$ would represent the probability that Taleyarkhan observed fusion, and $P(B)$ would represent the likelihood that evidence of fusion would exist.

Unfortunately, the probability of each of these items is much less intuitive than the example of our psychic friend. $P(B \mid A)$ seeks to address the likelihood of a replication

[2]In this particular example, calculating $P(B)$ from 12 rolls of the die produces a probability that is greater than 1. This is merely a result of the assumptions made about the denominator, $P(B)$. According to the Law of Total Probability, $P(B \mid A)\,P(A)$ should never be greater than $P(B)$, since $P(B) = P(B \mid A)\,P(A) + P(B \mid \neg A)\,P(\neg A)$.

attempt succeeding if it were certain that Taleyarkhan had observed fusion. While this should, in theory, be 100%, Taleyarkhan himself would likely disagree. Even if Taleyarkhan had achieved fusion, it may be possible that another experiment seeking to replicate these results would not be able to. If we are to accept this as a possibility, then $P(B \mid A)$ cannot be 100%. Erring on the on the safe side, perhaps this would occur approximately one-in-ten times. Therefore, $P(B \mid A) = .9$. Moving on, $P(A)$ needs to reflect the extra-ordinariness of Taleyarkhan's fusion claim. We know from the extreme conditions required that the claim of fusion is already unlikely, and the claim that fusion could be achieved in a table-top apparatus, rather than a large-scale fusion reactor like the ITER even further decreases these odds. If we loosely assume that the probability of successful net energy positive fusion from the ITER is about one-in-1,000, and that the ITER apparatus is about 100,000 times more likely to produce fusion than a table-top one, then we arrive at a highly approximated, but conveniently simple, probability of $P(A) = \frac{1}{1{,}000{,}000}$.

That leaves $P(B)$ to be accounted for. From the Law of Total Probability, $P(B)$ can be expanded to

$$P(B) = P(B \mid A)\, P(A) + P(B \mid \neg A)\, P(\neg A)$$

We know from above that $P(B \mid A)\, P(A) = .9 \times \frac{1}{1{,}000{,}000}$, and that $P(\neg A) = 1 - P(A) = \frac{999{,}999}{1{,}000{,}000}$, so what remains to be assigned a value is $P(B \mid \neg A)$, or the liklihood that the evidence exists given that Taleyarkhan's claim was false. In a perfect scientific world, we would hope that this value would be zero. If an original claim is incorrect, then no replication attempt should be able to produce a confirmatory result. Unfortunately, false-positives do exist, and the more speculation and inference that goes into a result, the more likely a false-positive will be. With that, could it be possible to a replication attempt to report positive findings even if Taleyarkhan truly did not? If so, how likely? This answer to this becomes the variable that dictates the extraordinary nature of the evidence.

p n	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
0.3	0.0000	0.0000	0.0000	0.0001	0.0004	0.0012	0.0041	0.0135	0.0437	0.1323
0.2	0.0000	0.0000	0.0001	0.0006	0.0028	0.0139	0.0657	0.2601	0.6374	0.8978
0.1	0.0000	0.0001	0.0009	0.0089	0.0826	0.4737	**0.9000**	**0.9890**	**0.9989**	**0.9999**
0.01	0.0001	0.0089	0.4737	**0.9890**	**0.9999**	**1.0000**	1.0000	1.0000	1.0000	1.0000
0.001	0.0009	0.4737	**0.9989**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000
0.0001	0.0089	**0.9890**	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

Table 4.1: $P(A \mid B)$, for n-number of positive, independent replications each with p-likelihood of being a false positive.

Rather than speculate on what this particular value should be, a sensitivity analysis can be used to calculate how various combinations of this probability and the number of replication attempts affect the calculation of $P(A \mid B)$. Table 4.1 demonstrates this. On the y-axis are various levels of $P(B \mid \neg A)$ for an individual positive replication, and on the x-axis are the number of positive replications.[3] Operating on the assumption that each positive replication occurs independently from one another, the cumulative value of $P(B \mid \neg A)$, where all the positive replication attempts are false-positives, would be the individual probability raised to the power of the number of replication attempts.This probability would then be multiplied by $P(\neg A)$ and then added to $P(B \mid A)\,P(A)$ to arrive at $P(B)$.

The stair-stepping border in Table 4.1 indicates values where $P(A \mid B)$, the likelihood that Taleyarkhan's claim is correct given the evidence presented, is greater than or equal to a 90% confidence level.

Two key observations can be made from this chart. The first is the exponential effect that the probability of a false-positive plays on the calculation of confident $P(A \mid B)$ value. For five positive, independent replication attempts, decreasing the probability of a false-positive from $p = .2$ to $p = .1$, only a 50% decrease, gives rise to an increase in the difference between a false-positive probability of .2 and .1 is an increase of $P(A \mid B)$ by nearly a factor of 30, from .0028 to .0826.

[3]The term "positive replication" is used here to define a replication that produces (positive) evidence in support of Taleyarkhan's claim.

The second is that, in spite of what traditional statistical intuition may say about significant sample sizes, at even a very high probability of a false-positive ($p = .3$), just over 10 positive, independent replication attempts would be required to overcome the extraordinariness of Taleyarkhan's claim of fusion – not 1000, 100, or even 30, as one may be led to expect. For very low values of the probability of a false positive ($p \leq .01$), only a few positive, independent replications would be needed to overcome the burden of proof created by the high unlikelihood of Taleyarkhan's claim.

Given the discussion earlier about the subjectivity introduced by the inference and supposition required in each replication, there would certainly seem to be a possibility of a false-positive replication, even if Taleyarkhan did not actually achieve fusion. However, liberally assuming that the probability that each positive replication could the result of a false positive falls in the range of $.01 \geq p \leq .2$, then at worst, only 11 positive, independent replications would be needed, and at best, just four.

So what insight does all of this statistical discussion provide into Taleyarkhan's claim of sonofusion and the evidence surrounds it. Put succinctly, given the evidence that exists currently, Taleyarkhan's claim does not fall above the line in Table 4.1. With respect to Sagan's statement, the evidence that exists in support of Taleyharkhan's claim of sonofusion is insufficient to justify such a claim. There's just not enough proof.

But why not? Perhaps Taleyarkhan's claim truly was false and he never actually observed evidence of fusion from sonoluminescence. And to be certain, the evidence that exists in the form of independent replications that could not produce positive, replicative results (Suslick, Shapira-Saltmarsh, and Putterman) increases the amount of evidence required above what is suggested in Table 4.1. But in spite of all of this, only seven replication attempts have been made *in total*. Taleyarkhan touts the simplicity of his experimental setup, and even Putterman was reported as having once used his own money to purchase the equipment necessary to build a sonoluminescence apparatus.[51]. In the best possible outcomes for

Taleyarkhan, some of these attempts may produce positive sonofusion results and some credibility may be added to the claim. But at worst, negative results would only further lay to rest the idea that sonofusion was impossible, and hopefully allow sonoluminescence research to move on.

Instead, the lack of popularity that any sonoluminescence-related publications have received since the Taleyarkhan fusion papers suggests that the research, especially in the applied field, has been stunted by the controversy surrounding sonofusion and the failure to properly lay the claim to rest.

While this may feel draconian, the reception of Taleyarkhan's publications significantly affected the popularity of sonoluminescence and sonoluminescence research as a whole in an extremely negative way. With the Gaitan single-bubble publication in 1990, sonoluminescence began to experience a Golden Age of research. As mentioned in the 2 chapter, scores of papers were published, a movie was released, and the British Broadcasting Corporation even funded the Seth Putterman lab to conduct sonoluminescence research. Taleyarkhan's fusion results, though, marked the end of this Golden Age.

To understand why, consider an engineer or physicist in 2006 looking to explore and begin an innovative new project. At this point in time, sonoluminesence would now be the last place he or she would want to look. As a direct result of Taleyarkhan's work and the news and media coverage that surrounded it, sonoluminescence and "sonofusion" have become all too easily synonymous. This would undoubtedly lead issues if and when one needed to seek funding. At the university level or national lab level, why would any research institution wish to associate itself with what had been publicly received with so much controversy? At the funding allocation level, why would any source of funding wish to allocate its resources to something which has received so much attention yet produced so little to show for? These claims are intentionally over-dramatized, but with the competitiveness of scientific grant funding, it should become how easily claims like these manifest.

This inevitably led to a decline in sonoluminescence research and publications, especially in the applied space. A cursory search through the first 10 results pages on Google Scholar for "Sonoluminescence Application" and "Applications of sonoluminescence" reveal a startlingly low number of relevant results that directly involve sonoluminescence. Though "about 4,450" results are returned, the overwhelming majority of these publications pertain to cavitation and sonochemistry, and simply note sonoluminescence as an observed and occasionally measured side effect. Very, very few papers involve sonoluminescence as the primary subject matter.

One search result was a paper titled "A Practical Application of Sonoluminescence to the Evaluation of The Cavitation Potential of the Mechanical Heart Valve," which suggested that sonoluminescence light production could be measured as a proxy for the presence of potentially damaging cavitation in artificial heart values.[59] Another, titled, "Multi-bubble Sonoluminescence: Laboratory curiosity, or real world application?" posited the novel idea of using sonoluminescence to activate photosensitizing drugs used to treat cancer cells.[60][4] It also suggests that sonoluminescence may have a purpose in destroying contaminants during the manufacturing process of semi-conductors, a claim that is further corroborated by a 2011 paper from the Japanese Journal of Applied Physics.[61].

In spite of how potentially viable these possible applications (and the few others not mentioned above) may be, no paper has received near the media or scientific attention that any of the Taleyarkhan papers received. Whereas Taleyarkhan's 2002, 2004, and 2006 papers have been cited (according to Google Scholar) 555, 186, and 146 times, respectively, both of the above papers have been referenced just once, each. Much of this can be attributed to the differences in popularity between the journals in which these findings were published. However, at least some has to be the result of the fact that scientists in the field have shied

[4] It interesting to note the timidity that comes across in this title. Despite the sound overview of Sonoluminescence that the article offers, "Laboratory curiosity" reads as if the authors were attempting to hedge against the claim of sonoluminescence's uselessness

away from sonoluminescence as a direct result of Taleyarkahn's fusion research and the way the academic community responded to it.

Chapter 5

The Path Forward

With interest and publications surrounding sonoluminescence having declined in the years following 2006 and the Taleyarkhan findings, an empty space was created in the field. While much progress has been made in the way of identifying and attempting to understand the underlying mechanisms of the phenomenon, there has yet to be another, ground-breaking and news-worthy discovery or publication regarding sonoluminescence. Such a discovery, however, might already have been made and simply needs to be brought to light.

Initially published in 1989 in the Journal of Soviet Physics Acoustics, a Russian (then Soviet Union) scientist at the Russian Institute of Applied Physics by the name of Vladimir Chernov presented findings that suggested sonoluminescence could be used as a blood-based medical diagnostic and screening tool. In the paper, titled "Ultrasonic luminescence of blood plasma and the diagnosis of cancer," Chernov and co-authors S.M. Gorskii, I.D. Karev, I.G. Terent'ev conducted "422 luminescence measurements...on blood plasma from donors, from patients with various chronic illnesses, and from patients with primary cancer localizations (in the stomachs, in the lungs, etc). [62] The sonoluminesence intensity measurements over time are reproduced in Figure 5.1. Reportedly, a clear difference exists between line a, blood donors (negative control); line b, "patients with chronic diseases of nonmalignant genesis";

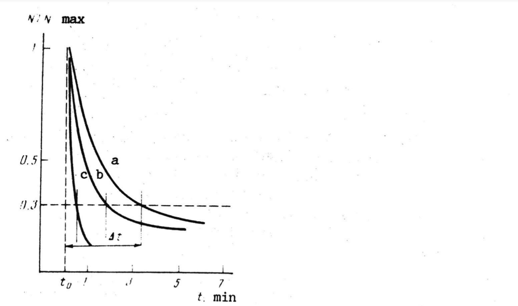


FIG. 1. Normalized luminescence intensity vs time at a constant ultrasonic excitation amplitude for blood plasma from: a) Blood donors; b) patients with chronic diseases of nonmalignant genesis; c) cancer patients.

Figure 5.1: From Chernov et al., Normalized Sonoluminescence Intensity over time for three types of patients.[62]

and line c, patients with cancer.[62]

Chernov et. al further supported this finding with another publication in 2003, published this time in Volule 6 of the Hydroacoustics Annual Journal. This article, "Sonoluminescence of water and biological fluids" tells a smiliar story. This time, 465 patients were tested, where 395 (84.9 %) were considered pathological and 70 were healthy.[63]. Figure 5.2 depicts Chernov's results for one set of patients.[63] The top three curves represent normal blood plasma patients (control) the second from the bottom is from a patient with "cancer blood plasma;" the bottom is a patient with AIDS. This result is particular intriguing, for each of the three sets of curves differs significantly from one another. This significant difference is made even more apparent in Figure 5.3, which plots the sonoluminescence Index, K, which normalizes outputs against a negative control of distilled water.[63] Though the lower bound of the error bar is not discernible, assuming the lower tail matches the upper, the sonoluminescence Index of each disease group appears to be significantly different from one another.

From a combination of the two papers, it can best be deduced that Chernov's measurement process resembled something of the following:

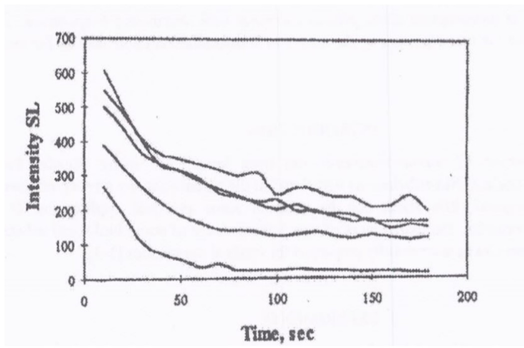


Figure 5.2: Dependency of sonoluminescence intensity over time for five different patients. The Y-axis represents sonoluminescence intensity by way of photon count, and the X-axis represents time.[63]

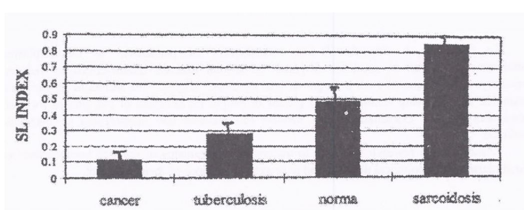


Figure 5.3: Distribution of the sonoluminescence index across different diseases and control (normal) group.[63]

1. Draw blood from patients
2. Isolate blood plasma from blood sample
3. Leave blood plasma in contact with air for at least 1, 24 hour day
4. Expose blood plasma sample to driving frequencies of 350 kHz, 530 kHz, and 780 kHz at a power no greater than 10 W
5. Measure sonoluminescence intensity (number of photons) every 10 seconds (averaging period) in the 300 nm to 700 nm range emitted from the sample over time
6. Compare the Intensity/time plot against known samples

In short, these two papers indicate sonoluminescence could be effectively used to screen for, and even potentially diagnose a number of communicable diseases and cancers. As will be explored later in Chapter 6, the implications of such a device would be revolutionary. Shockingly, though, nothing came out of these two papers. None of the leading sonoluminescence researchers mention either paper in recent publications, and Google Scholar indicates that the 2003 paper has only been cited one time, in specific by a paper published in Russian.

Even more interestingly, Vladimir Chernov appears to have published no other papers involving sonoluminescence past 2003, and no papers at all past 2008.[64] [1] Additionally, in an effort to seek further information about these findings and the experimental setups used, the author of this thesis has made multiple unsuccessful attempts to contact him. This was done both through the email address listed on his publications and through his email addresses co-authors and contributors on other papers. These emails were sent both in English and in Russian, but neither language has elicited a response from any of the

[1] The Kuehne Physics Mathematics Astronomy Library at The University of Texas at Austin contains a complete collection of Soviet Physics Acoustics journals from 1970 to 1989. In the entire 20 year collection, Chernov's name only appears three times. Once in 1980 in a paper titled "Singular features of the ultrasonic fluorescence spectrum of water", once in 1985 in a paper titled "Influence of oxygen on the intensity and spectrum of the ultrasonic fluorescence of water," and once in the paper cited above.

contacted authors. Attempts were even made to locate Chernov through contact information provided by the Russian Institute of Applied Physics and the Russian Academy of Sciences. These too have been unsuccessful. Chernov, as of the writing of this thesis, seems to no longer exist.

However, while neither Chernov nor any other scientist appears to have made an attempt to replicate his 1989 and 2003 findings, a variety of other publications have since come along that offer strong indirect support of the validity of sonoluminescence as a blood-based screening and diagnostic tool.

Most notably was the 2016 publication of a paper entitled *Diagnosis and Classification of 17 Diseases from 1404 Subjects via Pattern Analysis of Exhaled Molecules* published in the ASC Nano journal. [65]. In particular, Nakhleh et al. “report on an artificially intelligent nanoarray based on molecularly modified gold nanoparticles and a random network of single-walled carbon nanotubes for noninvasive diagnosis and classification of a number of diseases from exhaled breath.” [65] Specifically, Nakhleh et al. built a quasi- “breathalyzer,” which could, with a high degree of accuracy, diagnose and classify one of seventeen different diseases that the patient may have had.

Though the authors of the paper report that the“breathalyzer” is being researched and make no indication of when it may commercialized or made available to medical institutions, the implications of such a device are massive. Human breath is readily available in all patients and can be obtained almost effortlessly and with little to no risk of concern of spreading contagious or communicable diseases. Equally importantly, such a device also significantly reduces the financial and educational barriers to entry associated with the other methods of screening for and diagnosing these diseases. Of the seventeen different diseases explored in the paper, eight were types of cancers, which would traditionally require radiology tests, endoscopy procedures, and/or biopsy tests.[66] To a patient without insurance, endoscopy tests can easily costs thousands of dollars. Biopsies and radiology tests, while cheaper, are also still cost-prohibitive to many. Likewise, each of these tests involves a combination of trained nurses, doctors, and lab technicians. As a result, the opportunity for a device that could reduce either of these costs is massive. And, owing to the massive publicity that this article has received, the public seems to be equally understanding of this significance. These costs will be further explored in Chapter 6.

Returning to the publication, Nakhleh et al.'s apparatus differentiated between each disease through measurable differences in volume of a variety of different volatile organic compounds. According to the American Lung Association, Volatile Organic Compounds, or VOCs, are highly evaporative gasses emitted from certain solids or liquids, which may have short term and long term adverse health affects.[67]. Many commercial and industrial processes emit these gasses, which are then absorbed into the body when one interacts with and breathes the air into which they have evaporated. [2]

Summarizing the Nakhleh paper heavily, a pattern of volumes and concentrations of VOCs were discerned for each of the 17 diseases, and then the breath sample entered into the apparatus would then be algorithmically compared to this pattern, and the pattern with which the sample matched most closely would be returned as a possible match and diagnosis. Put more simply, minute differences in chemical concentrations of the breath sample could be used to, with a high degree of accuracy, diagnose a patient with one of 17 different diseases.

Thus, just as Nakhleh found with breath, minute differences in chemical concentrations of a blood sample could, reportedly, be used to screen for or diagnose a variety of different diseases. Excitingly, though, the connections between these two reports did not simply end with the processes or the results.

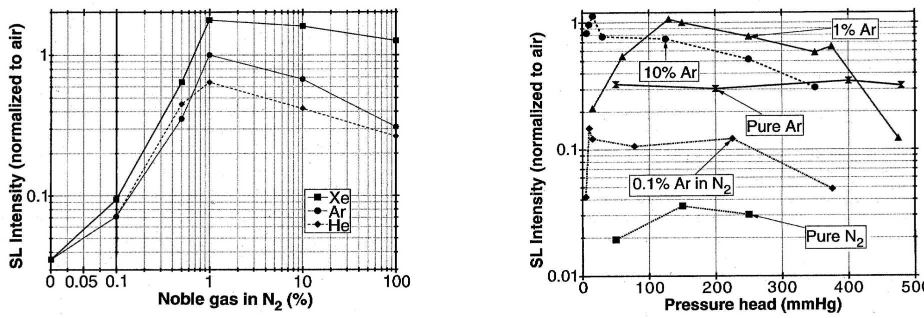
[2]For a complete list of Volatile Organic Compounds and their specific health effects, see the Agency for Toxic Substances and Disease Registry Toxic Substances Portal, found here: `https://www.atsdr.cdc.gov/substances/index.asp`

Regarding the connection between these two experiments, the first is that of VOCs in breath and blood. Literature exists that connects the the presence and concentration of VOCs in breath with VOCs in blood. Mochalski et al. and O'Hara et al. both posit that a correlation exists between the concentration of VOCs in blood and the concentration of VOCs in breath. The Mochalski study notes that 12 of the 74 compounds (16.2%) were "simultaneously present in both fluids (> 90% occurrence)." [68]. However, O'Hara et al. does express replication concerns with respect to the measurement of VOCs in blood, noting that the "coefficients of repeatability as a percentage of mean are less than 30% in breath but greater than 70% in blood."[69].

While 12 out of 74 is admittedly lower than desired, the point of drawing connection is not to demonstrate how similar the VOC concentrations are between blood and breath. Instead, the fact that this number is non-zero should be received as positive evidence that there is *some* connection the chemical composition of breath and the chemical composition of blood.

Second, abundant research exists detailing the effect of dissolved gasses on sonoluminescence intensity and spectral output. This effect was observed and published in 1994 by Hiller et al., specifically about the effect of noble gasses on sonoluminescence. In specific, Hiller et al. note, "increasing the noble gas content of a nitrogen bubble to about 1% dramatically stabilizes the bubble motion and increases the light emission by over an order of magnitude to a value that exceeds the sonoliminescence of either gas alone." [70] Figure 5.4 demonstrates a clear difference in normalized Sonoluminescence light intensity with respect to concentration of argon relative to nitrogen, and also a clear difference in how different pressures at which the noble gas was dissolved into the bubble affect Sonoluminescence intensity for different dissolved concentrations of dissolved argon.

This effect of gaseous content on sonoluminescence intensity was further explored by a a 2016 paper published in Ultrasonics Sonochemistry entitled *Influence of dissolved gases*



(a) SL intensity vs. gas concentration[70]

(b) SL intensity vs pressure[70]

Figure 5.4: From Hiller et al, effect of concentration (left) and pressure (right) on SL Intensity.[70]

on sonochemistry and sonoluminescence in a flow reactor.[71]. Here, the effect of dissolved argon, air, nitrogen, and carbon dioxide Sonoluminescence yield was examined in terms of the number of photons observed over a 30 second period using a a photon counting head.

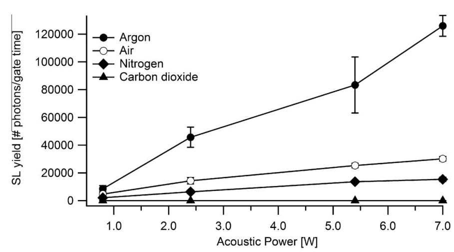


Figure 5.5: From Gielen et al., Sonoluminescence yield, displayed as the number of photons per gate time, as a function of the acoustic power for different gases at a frequency of 248 kHz.[71]

Graphical representation of these differences Figure 5.5 and Figure 5.6, reproduced from Gielen et al., show the results of this experiment at frequencies of 248 kHz and 47 kHz, respectively.[3]. With the exception of measurements at .8 W, all measurements of photon counts were significantly different from each other. As with the link between chemical

[3] As noted by Gielen et al. At all power levels at both frequencies, solid lines shown connecting measurement points were added to aid in the detection of a trend and do not represent any measurement or model

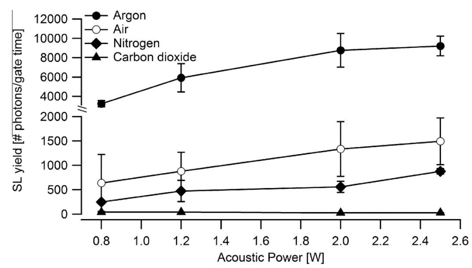


Figure 5.6: From Gielen e. al., Sonoluminescence yield, displayed as amount of photons per gate time, as a function of the acoustic power for different gases at a frequency of 47 kHz.[71]

compound concentrations in blood and breath, it is again important to note the observed differences in output in Figures 5.5 and 5.6 are not an attempt to provide a causative explanation of the differences in sonoluminescence output from the Chernov experiment. Rather, these figures, and the Gielen study as a whole, is included merely to show that literature exists that confirms the dependency of sonoluminescence output on dissolved gasses, but not necessarily any gasses in particular.

In summary, then, it is known from existing, peer-reviewed literature that:

- Chemical composition in breath can be used to screen for and diagnose different diseases
- A connection exists between chemicals in breath and chemicals in blood
- Sonoluminescence output is heavily dependent upon the type and concentration of dissolved gasses in the fluid medium

Thus, despite the limited information that the Chernov papers provide, and the lack of any documented attempts to replicate the experiments, the literature peripheral to blood as a screening and diagnostic tool affords a degree of viability to Chernov's findings. And, even if the possibility of this viability is quite small, the implications of a successful device, as will be seen in the next chapter, easily warrant and demand further investigation into Chernov's work.

Chapter 6

Value of a Screening Device

Implications for Patient Costs

Financial implications from a successful device While the current absolute costs associated with tests for HIV/AIDS Tuberculosis (TB) may not rival those mentioned earlier in the present manuscript, the per patient price can nonetheless be cost prohibitive to many seeking HIV/AIDS or TB tests, and is often unfortunately the most cost prohibitive for those patients who need the tests the most. A 2015 study into the costs associated with implementing rapid HIV testing, currently the most common HIV test, found that median per patient costs for the test were $ 22 without counseling and $ 46 with counseling.[1][72]

TB - Financial implications from a successful device The same story is true of Tuberculosis tests. While not necessarily as expensive as a cancer test or screening may be, their price can certainly still expensive enough to be cost prohibitive to some populations. The San Francisco Department of Public Health conveniently lists out the cost of various TB tests administered at their AITC public health clinic. As of January 23, 2019, the cost

[1] It should be noted that these two values represent a median price from a relatively small sample size ($n = 7$) and in 2015. Academic literature suggests that the price of these tests has certainly come down over the past decade, but the author was unable to find a reliable statistic for nationwide trends in HIV tests).

Test Type	Return Visits?	Price
PPD Skin Test	Yes	$49
2-Step PPD SKin Test	Yes	$98
Quantiferon TB-Gold In-Tube (blood test)	No	$107
Risk Assessment for SEs and Volunteers[2]	No	$49

Table 6.1: San Francisco AITC Tuberculosis Test Costs. See [73].

for each type of TB test are shown in Table 6.1

Thus, an apparatus that would allow for a low cost screening for both of these tests would be highly valuable. And, if Chernov's implications hold, then a device that uses sonoluminescence could be the solution. With an easily obtainable input (blood plasma) and and a clearly interpretable output (presumably a light intensity per time curve), the costs associated with administering each test and maintaining the apparatus would hopefully be quite low. Moreover, this nature of the device, in that it could screen for multiple different diseases, could further compound this cost saving. If a patient is concerned that he or she may have come in contact with a communicable disease, but is not necessarily sure which disease, a sonoluminescence test that could screen for multiple different diseases would could save such patients both time and money, and then allow him or her to make a more informed decision about which test to pursue next, if necessary.

Implications for Testing Procedures

Regarding time savings, a sonoluminescence screening device also presents the unique possibility for reducing the lag time that currently exists between exposure to the HIV and when HIV testing will become accurate. The soonest the rapid HIV testing mentioned in Section 6 will be able to detect infection is 3 weeks, with approximately 97% of people developing detectable antibodies within 12 weeks.[74]. Other tests, such as fourth-generation tests that search for both HIV antibodies and antigens are becoming increasingly popular and have a slightly reduced latency of 2 to 6 weeks, but still leave room for improvement[3]

The significance of this convenience is further brought to light one one considers that patients seeking Tuberculosis screenings or testings are frequently those who are most susceptible to HIV/AIDS. The Center for Disease Control states that "HIV infection is the most important risk factor for progression from latent TB infection to TB disease."[75]. Thus, a need exists in the healthcare market place for consolidated testing, or screening, for both of these diseases.

TBfacts.org, a website offering information about tuberculosis, offers even more striking evidence of this need. While many of the statistics on this website are admittedly dated, one stands out in particular. In 2012, " 55% of notified TB patients had a documented HIV test result," which represents "an 18 fold increase in testing coverage since 2004'." [76]. Quite simply, the world needs a device that can quickly and cheaply screen for HIV and TB.

Implications for Health Clinics

Bigger picture implications However, the per patient cost fails to paint the complete picture of the potentially prohibitive costs associated administering HIV and/or TB tests. While the patient obviously encounters the per patient costs listed above, there are a number of significant overhead costs associated with both opening and operating clinic capable. A cursory search of the phase "HIV and Tuberculosis Testing Texas" failed to reveal any clinic or testing location that administered both tests.

A sonoluminescence based screening tool, were it to work as posited in Chapter 5, would significantly encourage the creation of such clinics. Such a device would afford the ability of

[3] A third option, the nucleic acid test, would likely offer the lowest latency between exposure and testability, with results available in as little as 1 week after exposure. This test was not mentioned here because it is highly expensive, requires significant infrastructure and expertise, and is only recommended in very specific situations. More information on the test and its drawbacks can be found here and here.

a patient to screen for a multitude of diseases, rather than individually at separate clinics. With a high enough degree of accuracy, the healthcare provider and patient could then use this information to more efficiently recommend whether or not the patient should pursue further testing for a disease, and if so, which disease and which tests to pursue.

This provides a benefit to all components of the healthcare network. The expected value associated with screening and testing costs decreases at a per patient basis, because the likelihood of needing a test is reduced in cases where the sonoluminescence screening result returns negative. On the provider side, the knowledge that patients being tested are predisposed to an increased likelihood of testing positive could potentially be useful information that could aid in the reduction of false positives, as the cases that do receive formal diagnostic tests would have the increased confidence of a positive result from the sonoluminescence screening. [75]

Implications for Low Income and Developing Nations

Returning to a point made earlier in Section 6, a Sonoluminescence HIV/TB screening apparatus would be extremely useful in developing, low income nations, where sources are lacking both on the patient and the provider end. Whereas 55% of worldwide TB patients had a documented HIV test result in 2012, "in the African region where the burden of HIV associated TB is highest, 81% of TB patients had a documented TB test."[76] If the world needs a quick HIV and TB screening device, then areas with a high incidence rate of HIV needs such a device even more. Likewise, from the same source, one can see that of the 374,000 recorded TB moralities in 2016, a striking 230,000 (61%) occurred in Africa.[76].[4]

And, though the evidence is weak at best, the Chernov publications offer the possibility that a sonoluminescence apparatus could even be made to fit into an object roughly the size

[4] A more robust overview of the HIV and TB testing protocol and clinic flow in South Africa, specifically, can be found here[77]

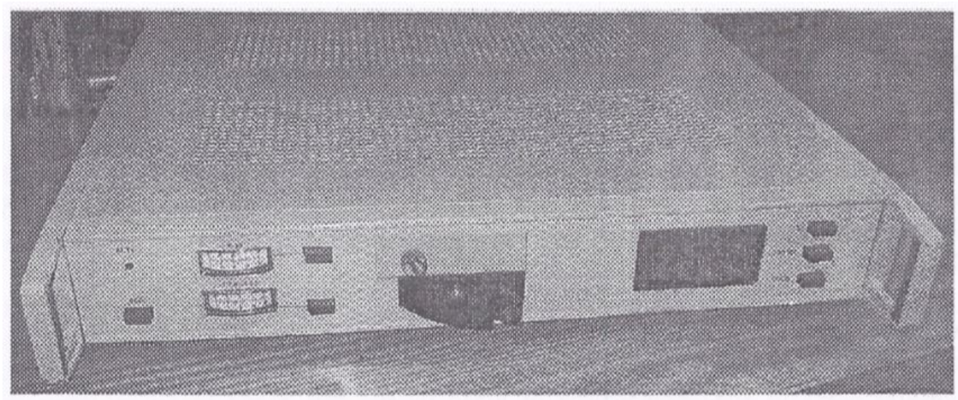


Figure 6.1: Chernov's "Diagnostic sonoluminescence device" [78]

of a small briefcase or a large suitcase, as seen in Figure 6.1. If such a build is possible, then the portability of such an apparatus even further increases its significance and viability in a location that may not yet have permanent testing clinics constructed or operating.

Chapter 7

Experimental

With the social, medical, and financial implications a blood-based sonoluminescence tool further unpacked, an attempt to replicate Chernov's results seems warranted. In order to achieve this, a device capable of producing stable, consistently, and measurable sonoluminescence would be necessary.

Apparatus #1

The first effort to build a sonoluminescence apparatus for this project took place during the summer of 2016, immediately following the semester in which I took TC310, as explained further in the Foreword of this thesis. With the subject fresh on the mind, initial goal was simply to construct an apparatus capable of producing some sort of sonoluminescence, whether it be single-bubble, or multi-bubble. This attempt loosely followed an apparatus and schematic provided by a paper published in the Journal of Molecular and Quantum Acoustics in 2007 by Boczar et al. Owing primarily to the youthfulness, the Boczar paper was selected primarily because an image, reproduced in Figure 7.1, offered a tangible, visible goal for what a success case should look like.

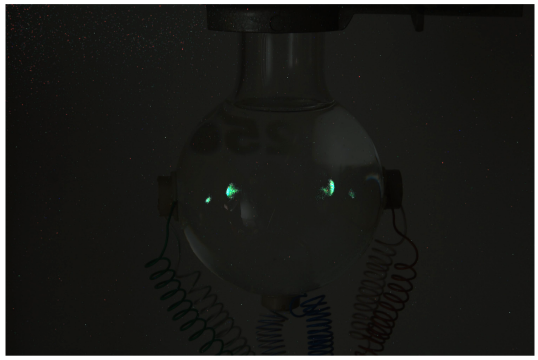


Figure 7.1: From Boczar et al., "Sonoluminescence light in a 133 kHz ultrasound driven 250 ml flask." [79]

In addition to the Boczar schematic, a number of other sonoluminescence "How-To" guides, all available online, were referenced. These included an web page published on techmind.org, one published by a German Scientist named Reinhard Geisler,an anonymous lab report published by the University of Rochester's Department of Physics and Astronomy, and an article published in the February 1995 issue of Scientific American by the previously referenced physicists Robert Hiller and Bradley Barber. Links to each of these articles are provided in the footnotes.[1]

Because this initial attempt was intended merely as a proof-of-concept that sonoluminescence and a device capable of sonoluminescence production were real and achievable, more effort was placed on simply constructing a device that could produce the phenomenon and less on accurately measuring and recording any light output. Furthermore, and again due to the youthfulness of this project, funding for this iteration of an apparatus was more limited. As a result, the majority of the parts and equipment obtained and used were either those already available for public use in a lab space, or the cheapest available that could reasonably be expected to function.

[1] Techmind.org: http://www.techmind.org/sl/, Reinhard Geisler: /urlhttp://www.macgeisler.de/nld/sbsl-howto.html, University of Rochester report: http://www.pas.rochester.edu/~advlab/11-Sonolum/sono1.pdf, Scientific American article: https://www.slideshare.net/DolonPal/bubbles-turn-sound-into-light-by-scientific-american-magazine

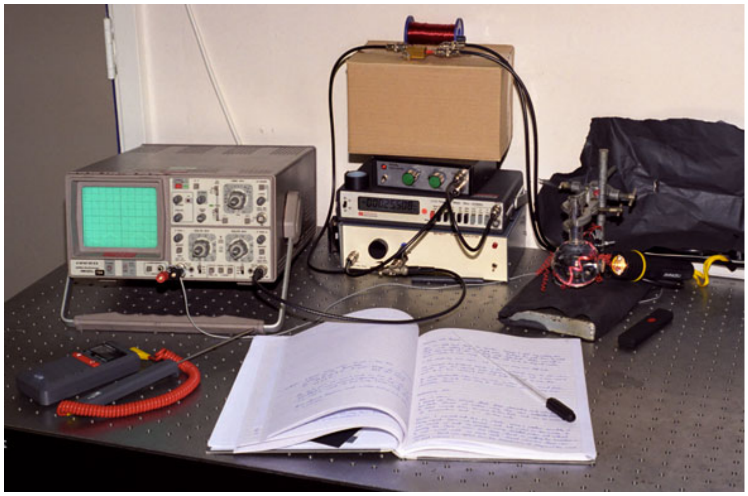


Figure 7.2: Techmind.org experimental setup[80]

Moreover, a number of physical constraints dictated the setup of this iteration. Because no permanent lab space yet existed for this project, any device constructed needed to be both portable enough to bring back-and-forth to the temporary lab space that was used at the time and small enough that it could be stored in the corner an office or tucked away in a medium sized cabinet in that lab space.[2]

It should be noted, though, that despite the significant limitations associated with this attempt, successful sonoluminescence generation was still a reasonable expectation. The list of materials from each of the three articles suggested sonoluminescence should be capable within this budget, and images from the Geisler write-up and Scientific American article, reproduced in Figure 7.2 and Figure 7.3, respectively, were mirrored rather closely by the apparatus that was constructed, as seen in Figure 7.4.[3]

[2]The author is especially grateful to the UT Makerspace and its staff, which provided access to function generators, electrical equipment, table space, and storage for this first apparatus. The staff even offered multiple times to turn off the lights in order to test for light emission.

[3]The astute observer will note the absence of an audio amplifier in this setup. During use, an issue with the amplifier gave rise to a small electrical fire which forced the its removal from the setup prior to the taking of this photo.

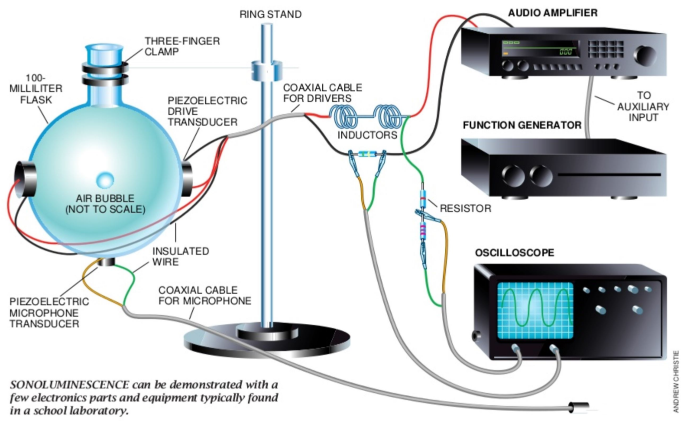


Figure 7.3: Scientific American schematic[81]

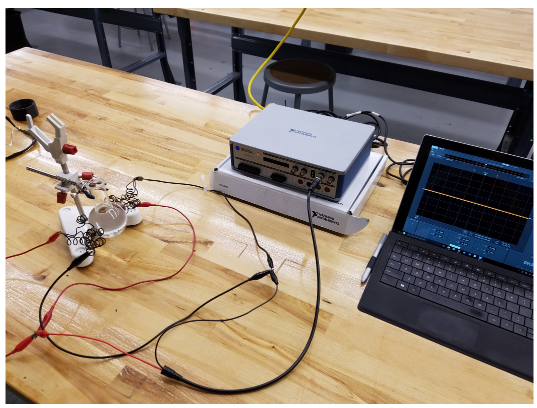


Figure 7.4: Experimental setup of Summer 2016 attempt (prior to addition of amplifier)

Ultimately, this first attempt at constructing an apparatus was a failure, insofar as it was not able to produce visually apparent sonoluminescence. Nevertheless, the experiment did succeed with respect to the fact that it was able to produce cavitation (which was audibly observed), and more importantly, served as enough of a proof of concept to further propel the project forward and begin the discussion about seeking out the appropriate resources to build a more robust sonolumunescence apparatus.

Apparaus #2

As a result of the enthusiasm created by a the first attempt at a sonoluminescence apparatus, the decision was made to pursue a more robust and scientific apparatus. With the help of University of Texas professor Roy Schwitters, a formal introduction was made between the involved parties of this project and researchers and professors at the Applied Research Laboratories and the University of Texas' Acoustics graduate program. Following consultation and oversight from these professors, namely Dr. Preston Wilson and Dr. Mark Hamilton, it was decided that the second attempt at a sonoluminescence apparatus would follow the specifications laid out in a Boston University masters thesis submitted by Ryan McCormick. Unlike the Boczar or Gielen papers, The McCormick is rich with detail and and instructions on how its specific apparatus was constructed. As a cursory overview, Figure 7.5 reproduces McCormick's diagram of his experimental setup

A cursory search through the McCormick thesis will reveal, though, that no mention of "sonoluminescence" exists in the entire 148 page document. In fact, the goal of the McCormick's work presented in the thesis was not to experiment with or generate sonolumienscence at all. Instead, the goal was to measure bubble dynamics in a xantham gel to see whether the gel could be used as a suitable replacement for water in bubble experiments.

While this may initially seem to be at odds with the end-goal of creating sonoluminescence and eventually introducing biological fluids, the work and experiments presented in the McCormick thesis nevertheless offer a number of valuable stepping stones toward an apparatus capable of those initial goals. First, as mentioned above, it includes troves of specific information about how each apparatus was setup, constructed, or laid out. It includes schematics, labeled diagrams, dimensions for the bubble chamber, and the exact lab equipment that was used and why. It even goes into comically specific detail about how to degas water with a "'French Press' coffee carafe container with a magnetic stir bar."[82]

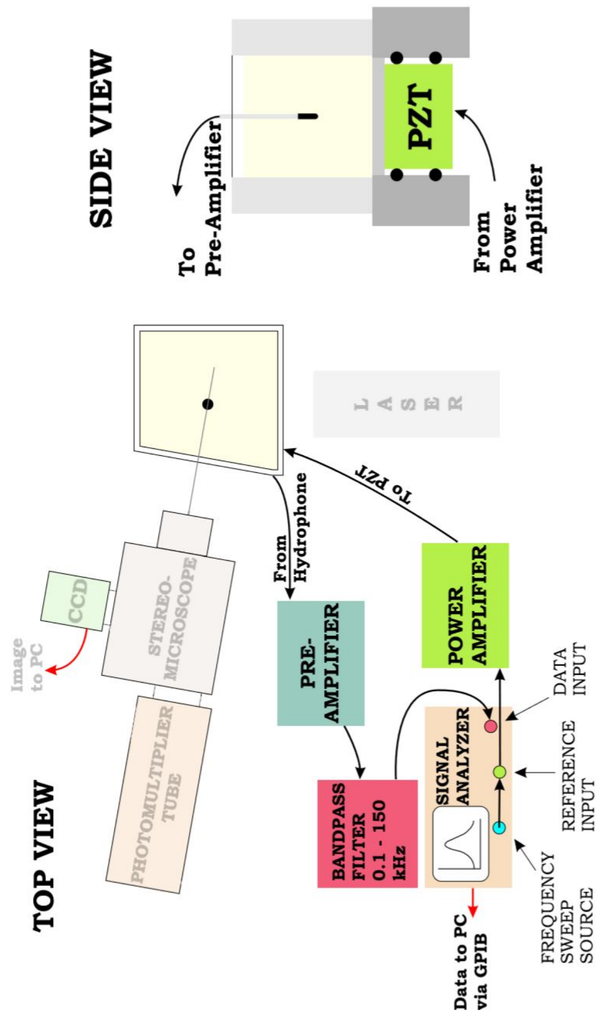


Figure 7.5: From McCormick, “Apparatus for optical measurement of the bubble response to acoustic forcing.”[82]

Second, the successful finding that bubbles and bubble dynamics do behave similarly in xanthan gel as water is also a valuable precursor to a sonoluminescence experiment. This removes the requirement to acoustically levitate a bubble in order to take accurate bubble measurements. This consequently allows for any measuring equipment used to be tested and calibrated in a more stable and controlled environment without potentially confounding background noise or sound which would otherwise have to be adjusted for.

As a result, it may be more appropriate to view the construction of an apparatus similar to the one created by McCormick as a stepping-stone to a successful sonoluminescence apparatus. By constructing this apparatus to the specifications laid out in the McCormick thesis, one can hopefully be confident that the electrical components and measurement tools are properly functioning before introducing the increased complexity of a sonoluminescing bubble.

Once this experimental setup is constructed and refined, the modular nature of the McCormick apparatus should allow for relatively easy substitution between the acoustic cell recommended by McCormick and another cell that may be more conducive to sonoluminescence production. Building the apparatus on an optical table or other vibrational control platform and placing the cell on a translation stage would also aid in the ease at which these components could be exchanged, as components that are to remain fixed can be bolted into place.

In regard to eventually conducting sonoluminescence experiments with diseased biological fluids, one potentially significant hurdle that will need to be overcome is the laboratory requirements necessary in order to safely conduct experiments involving these diseases and chemicals. At a minimum, experiments involving HIV/AIDS, Tuberculosis, and Cancer would require a Biological Safety Level (BSL) 2 laboratory, with some even necessitating a BSL-3 lab space.[83] Requirements for these laboratories range from simply personal protective equipment and a chemical disposal system to air-tight rooms with dedicated ventilation systems.[84]

Unsurprisingly, many engineering lab spaces where a sonoluminescence apparatus may be built will not have all or even any of these requirements. To address this, two suggestions are put forth below.

First, if possible, any sonoluminescence apparatus intended to interface with biological fluids should be constructed on a platform that can, with reasonable accommodation, be transported from lab-space to lab-space, and possibly from building to building, if needed. This may mean a smaller, dedicated optical table is used (if one elects to construct an apparatus on an optical table), and/or that construction of the apparatus should be heavily documented in such a way that it could, if absolutely necessary, be deconstructed and reconstructed in another location.

Second, though not fully explored in this project, the academic literature surrounding artificial and synthetic blood and blood plasma suggests these may be possible substitute that would potentially allow an experiment to bypass the BSL requirements laid out above.[85][86] Hypothetically, using the volatile organic compound concentrations observed in the Nakhleh et al. "breathalyzer" experiment, an artificial diseased blood plasma could be reverse-engineered by infusing a synthetic blood sample with the VOC concentrations.[65] At the time of writing, this idea is purely a supposition, as there is a high likelihood that any of the chemical and chemical property differences between this artificial sample and a biological sample would significantly affect the sonoluminescence intensity. The author leaves further exploration of this idea to future researchers.

Appendix A

The Taleyarkhan Investigations: 2006-2008

Unfortunately for Taleyarkhan, despite what his 2006 paper claimed to offer with respect to sonofusion, it faltered in its opening sentence, which claimed that "these observations [of neutron emission and tritium production during external neutron-seeded cavitation] have now been independently confirmed."[55]. The source cited here by Taleyarkhan was February 2005 paper written in the Journal of Nuclear Engineering and Design by Purdue researchers Yiban Xu and Adam Butt. At the time, Xu was a postdoctoral researcher working under Taleyarkhan, and Butt was a graduate student.

In this paper, "Confimatory experiments for nuclear emissions during acoustic cativation," Xu and Butt espoused Taleyarkhan's fusion claims, reporting that "Statistically significant (5–11 σ increased) emissions of 2.45 MeV neutrons and tritium were measured during cavitation experiments with chilled deuterated acetone."[87]

Lefteri Tsouaklas, then still the Head of the School of Nuclear Engineering, initially supported the legitimacy of the Xu-Butt paper, responding to an inquiring freelance reporter working an article for Nature that he (Tsoukalas)' "absolutely nothing to do with the paper or the work reported."[49]. This did not stop Tsoukalas himself from continuing to investigate. On February 7, 2006, Tsoukalas contacted Chan Choi, another faculaty member in the Purdue Nuclear Engineering department, with the intent of creating a "fact-finding committee" to investigate the Xu-Butt paper and Taleyarkhan's ties to it.[88] In question was "issues surrounding the data reported, the method of analysis, the actual authorship and the conclusions stated." This culimnated in "allegations [ranging] from misconduct to ethical issues."[88]

On March 8, 2006, news broke that Purdue had begin to investigate complaints made by Tsoukalas about Taleyarkhan and his findings. One news article, written by Reuters, states that Tsoukalas and Tatjana Jevremovic (co-author of the 2006 Tsoukalas fusion paper) Taleyarkhan had "'removed equipment with which they were trying to replicate his work, claimed as "positive" experimental runs for which they never saw the raw data, and opposed the publication of their own negative results."'[89]. In addition, for the first time publicly, researchers from the Putterman group at UCLA suggested that Taleyarkhan's fusion observations may have been contaminated with Californium-252, a radioactive isotope of Californium known to produce over 170 million neutrons per minute per microgram.[90] Given that Californium-252 is such a well-known neutron source, such a claim very directly insinuates fraud and misconduct, for any nuclear scientist would know better than to have such a substance anywhere near an experiment which was measuring neutron production.

The investigations escalated four months later, when the Vice President for Research at Purdue announced that the allegations made by Tsoukalas and Jevremovic should treated as ""research misconduct' as defined by the University's policy on Integrity and Research," and that a committee was to be appointed investigate these allegations.[91]. This was to address the claims put forth by Tsoukalas and Jevremovic, but also the concerns about Taleyarkhan's involvement with the aforementioned Xu-Butt paper and another submitted by the two at the International Topical Meeting on Nuclear reactor Thermal-Hydraulics in

2005.

Initially, Taleyarkhan was acquitted by the Research Integrity Office, primarily on the basis that the committee pursuing the matter lacked sufficient evidence needed to substantiate the allegations made by Tsoukalas, Jevremovic, and Bertodano. This official acquittal came on December 15, 2006 by the Associate Vice President for Research of Purdue's Research Integrity Office, Peter Dunn. In a letter sent to Leah Jamieson, the Dean of the College of Engineering, Dunn write that ultimately "there [was] insufficient evidence to warrant further pursuit of the Bertodano and Tsoukalas allegation."[92]. Regarding the claim of misconduct, Dunn claimed that the committee did "not believe that the evidence points towards intent to mislead the scientific community."[92] To the latter, Dunn concluded that "Taleyarkhan has displayed what might be characterized most favorably as severe lack of judgment regarding his involvement with the 'independent confirmation' experiment performed by Dr. Y. Xu."[92]. In short, while Taleyarkhan's involvement was ill-advised and potentially disastrous, the evidence compiled by the investigation committee did not warrant the conclusion of misconduct or a lack of independent confirmation by Xu. However, wrote Dunn, "There is a clear danger that future such claims by Dr. Taleyarkhan will lack" the characteristics of independent confirmation laid out in the letter.[92][1]

This acquittal was short lived. On May 9, 2007, chairman of the House of Representatives chairman of the Subcommittee on Investigations and Oversight of the U.S. House Committee on Science and Technology requested that Purdue re-open the investigation in to research misconduct by Taleyarkhan and provide a report to the subcommittee.[93] This led to a complete re-opening of the investigation and ultimately to a 38 page report, which was delivered to the subcommittee on April 18, 2008. This investigation and report, unlike

[1] These characteristics were, according to Dunn, "1. The experimental apparatus with which the experiment was performed would be significantly different from that used in the initial experiments. 2. The experiment would be performed by scientists who were not associated with Purdue University, and certainly not by individuals having close relationships to Dr. Taleyarkhan. 3. The involvement by Dr. Taleyarkhan would be minimal."[92]

the initial investigation, *did* find Taleyarkhan guilty of research misconduct on two of eight allegations. These allegations, and their conclusions, are reproduced from the report in Figure A.1 and Figure A.2.

> *Allegation*
> *Dr. Taleyarkhan with falsifying intent caused Mr Adam Butt's name to be added to the author bylines of the papers even though Mr. Butt was not a significant contributor to the experiments, the data analyses, or the writing of the manuscripts.*
>
> *Conclusion*
> *The Committee concludes that the weight of the evidence shows that Dr. Taleyarkhan compelled the addition of Mr. Butt's name as an author on the NED and NURETH-11 publications knowing that Mr. Butt had not substantatively contributed to those publications in order to create an appearance of collaboration between Dr. Xu and Mr. Butt on the work. This is research misconduct.*

Figure A.1: Allegation A.2[94]

> *Allegation*
> *Dr Taleyarkhan with falsifying intent stated in the opening paragraph of his paper in Physical Review Letters 96:034301 (2006) that "these observations [referring to Science:295:1868 (2002)] have now been independently confirmed."*
>
> *Conclusion*
> *Based on the findings in this section and in the preceding sections, we find that Dr. Taleyarkhan;s claims of independent confirmation of his sonofusion results are simply not supported by the weight of the evidence of his extensive involvement in the NED and NURETH-11 research and publication. The direct assertion of independent confirmation in the PRL96 paper is falsification of the research record and is thus research misconduct.*

Figure A.2: Allegation B.2[94]

Purdue officially sanctioned Taleyarkhan on August 27, 2008 after rejecting his appeal.[95] In a letter written by the then Provost of Purdue, William Woodson, two punishments were conferred upon Taleyarkhan. First, he was stripped of professorship (Arden L. Bement, Jr. Professor of Nuclear Engineering).[96] Second, his status as a faculty member was limited to a three year probationary status as "Special Graduate Faculty."[96] This removed the permission to serve as an advising professor for graduate students, but still permitted his serving on graduate committees. Following this three year period, Taleyarkhan would be permitted, with supervision, to seek to restore his faculty status, but not his professorship title.[2] Emphasis was further added in the letter to assure that Taleyarkhan understood this sanctioning was punitive in nature, and was a direct result of his research conduct.

[2] As of May 2019, Taleyarkhan's faculty profile on Purdue's website is listed as "Professor - Nuclear Engineering, with Courtesy Appointment in the School of Heath Sciences." No mention is made of his sonofusion research.[97]

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Afterword

In the closing of this thesis, I would like to briefly mention two important developments that have occurred with respect to the work work presented here.

The first is the progress made by Alicia Casacchia in constructing our own sonoluminescence apparatus. At the time of writing this, an apparatus that follows the specifications laid out by the McCormick thesis has been constructed that should be capable of producing and measuring sonoluminescence. The goal of this project continues to be an eventual replication of Chernov's experiments, and so the construction of this apparatus represents a huge step towards that goal.

Second, some contact was finally made with Chernov in the weeks leading up to the submission of this thesis. In particular, Chernov's *ResearchGate* profile recently responded to my request for a full-text edition of another sonoluminescence paper that he had authored, titled "Ultrasonic luminescence of blood plasma in the differential diagnosis of rectal cancer." At the time of writing this, a reinvigorated effort is being made to contact him directly and inquire about his research. As this project continues to progress, it would be incredible to have him as a resource for exploring sonoluminescence and its medical applications.

Biography

Parker Thomas George was born in Plano, Texas on February 25, 1997 and moved with his family to Kingwood, Texas in 1999. He enrolled in the Plan II Honors program at The University of Texas at Austin in 2015 and pursued a dual degree in mechanical engineering until 2016, when he transferred into the Canfield Business Honors Program in the McCombs School of Business. In college, he raced for the Texas Cycling team, was a senior outrider in the SAWIAGOS ghost class, and was a member of the Undergraduate Business Council. He graduated in 2019 with a dual degree in Plan II and Business Honors and began working that summer as a management consultant with Oliver Wyman in Dallas, Texas.